Project: H2020-ICT-2014-2 5G NORMA

Project Name:

**5G Novel Radio Multiservice adaptive network Architecture (5G NORMA)**

# Deliverable D2.3
# Evaluation architecture design and socio-economic analysis - final report

| | | | |
|---|---|---|---|
| Date of delivery: | 31/12/2017 | Version: | 1.0 |
| Start date of Project: | 01/07/2015 | Duration: | 30 months |

## Document properties:

| | |
|---|---|
| **Document Number**: | H2020-ICT-2014-2 5G NORMA/D2.3 |
| **Document Title:** | Evaluation architecture design and socio-economic analysis - final report |
| **Editor(s):** | Julie Bradford (Real Wireless) |
| **Authors:** | Ade Ajibulu, Julie Bradford, Charles Chambers, Simon Fletcher, Anastasios Karousos, Kostas Konstantinou, Hassan Osman (Real Wireless), Heinz Droste, Juan Rendon Schneir, Gerd Zimmermann (Deutsche Telekom), Rafael Canto Palancar (Telefonica), Vincenzo Sciancalepore, Zarrar Yousaf (NEC), Peter Rost, Mark Doll (Nokia) |
| **Contractual Date of Delivery:** | 31/12/2017 |
| **Dissemination level:** | PU[1] |
| **Status:** | Draft |
| **Version:** | 1.0 |
| **File Name:** | 5G NORMA D2.3 |

## Revision History

| Revision | Date | Issued by | Description |
|---|---|---|---|
| 1.0 | 15/12/2017 | 5G NORMA WP2 | 1st issue for publication |

## Abstract


This is the final report for Work Package 2 (WP2) of the 5G NORMA project. This work package has examined use cases for the technical innovations delivered by 5G NORMA and performed a socio-economic assessment against these. This document builds on the technical evaluations of 5G NORMA already published by Work Package 3 in D3.3 by performing network dimensioning, cost, revenue and social benefits assessments around the same three evaluation cases considered there. These three evaluation cases comprise:

- A single tenant enhanced mobile broadband (eMBB) service only comparison between a cloudified radio access network (C-RAN) based on network function virtualisation (NFV)/software defined networking (SDN) approaches derived within 5G NORMA and a classical 4G RAN with a distributed infrastructure (D-RAN)
- An assessment of the economic benefits of multi-tenancy in 5G NORMA considering eMBB services alone
- An assessment of the economic benefits of multi-service support in 5G NORMA.

Our revenue and cost assessments center around dimensioning for each of the three evaluation cases to fit the growing demand for mobile services over the time period of 2020 to 2030 in a central London scenario. RAN costs based on network dimensioning for this scenario are combined with revenue forecasts to understand the return on investment associated with the 5G NORMA infrastructure.


---

[1] CO = Confidential, only members of the consortium (including the Commission Services)

PU = Public

5G NORMA and the introduction of virtualised flexible networks supporting network slicing and multi-tenancy promise to disrupt existing business models in the mobile industry by expanding the range of end-users of public mobile networks and providing opportunities for new entrants. This document discusses these changes in business model structure and stakeholder roles and identifies examples where traditional mobile network operators are already repositioning themselves in the ecosystem and engaging with a wider range of end customers and verticals.

Alongside the commercial implications of 5G NORMA this document also assesses the potential social benefits of such networks and the wider range of services they promise to deliver. We discuss the issue of potential public private partnerships and creating the right regulatory environment to help stimulate industry towards these potential benefits where the commercial business case may be less clear or contain short term risks. Finally, this document concludes with implications for verticals, mobile network operators and regulators in terms of unlocking the full socio-economic benefits of flexible 5G networks like 5G NORMA.

## Keywords

Socio-economic, mobile network dimensioning, RAN costs, 5G revenues, willingness to pay, social benefits, 5G business models, stakeholders, virtualisation, multi-tenancy, multi-service

# Executive Summary

This is the final report for Work Package 2 (WP2) of the 5G NORMA project. The 5G NORMA project is committed to the design of a virtualised, flexible 5G network architecture that supports network slicing.

Key benefits of this architecture approach are:

- Multi-tenancy – the ability to serve multiple service providers from a shared infrastructure set and obtain cost efficiencies via this network sharing approach (i.e. an economies of scale cost benefit).
- Multi-service support – the ability to provide a mix of services with varying quality of service (QoS) requirements, in terms of throughput, reliability and device density, from a single network platform. This can lead to cost efficiencies due to economies of scope (i.e. providing services with different spatial and temporal distributions from a shared infrastructure set) as well as new revenue streams beyond today's business to consumer, enhanced Mobile Broadband (eMBB) service focused mobile networks.

Technical proposals for 5G NORMA and evaluations of key performance indicators on networks performance have already been published in WPs 3, 4 and 5 with key findings and recommendations captured in Deliverable D3.3 [5GN-D33]. D3.3 also expands on the opportunity for 5G NORMA to support a new form of ecosystem consisting of three key layers of tenants, mobile service providers and infrastructure providers with a range of supplier stakeholders supporting these and opportunities for new entrants and new relationships across these layers.

This document builds on the work in D3.3 by:

- Assessing the commercial case for migration towards virtualised networks as envisaged by 5G NORMA. This includes forecasting the impact on existing eMBB end-user revenues and capturing potential new revenue streams from other non-eMBB service categories supported by 5G NORMA. A network dimensioning and cost modelling tool has also been developed in line with the topology and equipment sets required for both today's Distributed Radio Access Networks (D-RAN) and a virtualised 5G NORMA like network architecture, including processing on x86 architecture processors, termed cloudified RAN or C-RAN in this document. This allows corresponding network costs for an example central London deployment scenario to be compared with revenue forecasts to assess the commercial case for migration towards 5G NORMA like networks in a range of "evaluation cases".
- Assessing the potential social benefits brought by 5G NORMA via improvements to existing wireless services and the introduction of new services. The potential role of public private partnerships to unlock these social benefits in cases where the commercial case may be less clear or hold short term risks is also discussed.
- Presenting the new form of ecosystem that 5G NORMA enables and implications for stakeholder groups including:
    - How today's industry players might reposition themselves within this ecosystem to maximise value generation.
    - Implications for new end-users of mobile services and engagement between industry verticals and the mobile industry.
    - Opportunities for new entrants within this new ecosystem.
    - Key aspects raised by flexible, shared, virtualised 5G networks for regulators to consider and considerations on creating the right type of regulatory environment to unlock the significant social benefits promised by future mobile networks.

Note our commercial assessment of networks using the 5G NORMA proposed architecture is not meant to give a definitive answer on the business case for such networks as this is subject to the

assumptions of our analysis. In practice these assumptions will vary greatly between existing Mobile Network Operators (MNOs) and be limited by practicalities such as site availability. However, our analysis aims to show likely cost and revenue trends and to expose the issues in future network deployments which may add or reduce risk in the future business case for mobile network services. It should also be noted that our analysis is based on a central London scenario where we would expect the business case for new services to be most promising due to the high density of users.

**Key findings regarding the commercial case for eMBB only single tenant networks based on the 5G NORMA proposed architecture**

Within this study we have analysed the CAPEX and OPEX incurred over an 11-year period from 2020 to 2030 for deploying a C-RAN virtualised network compared with a D-RAN network to deliver eMBB services to consumer portable devices in a central London example environment. Both networks were based on a typical MNO with an 18% share of the eMBB market. We conclude that costs on an 11-year Total Cost of Ownership (TCO) basis are similar between the two options with C-RAN requiring higher CAPEX but lower OPEX for this scenario and found only a very marginal TCO penalty with C-RAN (approximately 2%). Sensitivity analysis showed this conclusion stood largely unchanged for the traffic growth levels, transport costs and edge cloud site costs ranges explored.

When the above eMBB only network costs were combined with our forecast eMBB revenues for the central London example area this showed a 6% return on investment (ROI) for our medium traffic and revenue scenario. Deploying a C-RAN network appeared to make little difference to the business case compared to a D-RAN network. However, we note that there is risk to the future eMBB business case with this positive ROI being very sensitive to:

- Revenue scenario
- Traffic growth

We note that within the eMBB market there is very limited scope for increased revenues per subscriber (which are driven by a consumer’s willingness to pay). However, there is significant scope for variation in eMBB traffic levels based on the range of forecasts available. This means that in a high revenue and high traffic scenario the ROI for eMBB over the study period could reduce to -11.9% due to limited scope for increased revenue but high network costs due to higher demand. However, in our low revenue and low traffic scenario network costs are greatly reduced while revenues are assumed to remain at existing levels which leads to a 35% ROI.

**Key findings regarding the commercial case for eMBB only multi-tenant networks based on the 5G NORMA proposed architecture**

Our cost analysis of two existing site portfolios becoming a shared network for two Mobile Service Providers (MSPs) (each with a typical eMBB market share of 18% each) has shown a reduction in TCO of 14% between 2020 and 2030. This is without decommissioning and consolidation of sites but rather applying multi-tenancy support or sharing (in terms of masts, antennas, RRHs, baseband processing, spectrum and core network) to any new or upgraded sites that merit it in this timescale. These shared sites have access to pooled spectrum from the parties sharing the site and hence are higher capacity than in dedicated sites with access only to spectrum from one party. The ability to deploy these higher capacity multi-tenant sites means that site densification can be done more efficiently than in dedicated networks with a reduction in the total number of antenna sites needed. This reduction in site count leads to savings in large cost components such as site rental.

Our sensitivity analysis shows that there is a balance to situations where sharing is more beneficial. If demand growth is low and site densification is not required there is less opportunity to deploy higher capacity multi-tenant sites. Instead consolidation of existing site portfolios and site de-commissioning is needed to see sharing gains in the shorter term. However, in a high demand case the macrocell layer may already be very dense in which case small cells, which are more challenging to share, may be relied upon more to relieve demand hotspots. Additionally, the sharing benefit to the 11-year TCO will become capped regardless of the number of MSPs sharing a site due to limitations on the amounts of spectrum that can be pooled whilst still maintaining safe radiation levels. In our analysis assuming 100 MHz of spectrum per MSP, cost savings were capped at approximately 15% regardless of expanding sharing from 2 to 3 or 4 MSPs due to no more than an assumed spectrum pool of 200MHz being permitted at any shared site.

While sharing of network infrastructure and equipment costs can be realised already with today's networks 5G multi-tenant networks take sharing to another level. Within 5G multi-tenant networks resources can be shared at a more granular level than today. Also, MSPs can implement their own sets of virtualised network functions on the shared network resources and as such can have more control and less compromise in terms of the quality of experience delivered.

In terms of our business case assessment for eMBB, this improved for our medium scenario from an ROI of 6% to 17% when sharing amongst two MSPs was applied. Therefore, multi-tenancy stands to reduce some of the risk observed in the eMBB only case observed earlier.

**Key findings regarding the commercial case for multi-service networks based on the 5G NORMA proposed architecture**

Finally, our cost analysis examined the impact of applying network slicing to support non-eMBB services such as smart meter services and Vehicle to Infrastructure (V2I) services (including high bandwidth infotainment, low bandwidth massive Machine Type Communications (mMTC) assisted driving services and high reliability semi-automated driving services). In the case of these services a 100% market share was assumed within the study area.

The cost of the network was mainly eMBB-driven with other non-eMBB services only contributing small volumes of traffic (i.e. with smart meters, semi-automated driving and assisted driving traffic volumes combined being only less than 4% of the eMBB traffic volume in total over the study period). However, we observed a disproportionate increase in the cost when compared to the demand of some non-eMBB services. For example, there is a 0.0070% increase in overall network traffic when the smart meter traffic is introduced, but a worst case 5.2% increase in the network cost, due to the early initial investment for building the sub-1GHz capability into the network to support deep indoor penetration.

Other non-eMBB services, were more easily accommodated on the existing eMBB network. These included semi-automated driving where the existing site density in the study area combined with gains from vehicle mounted antennas were enough to provide the higher coverage confidence required for these services without any repurposing of the network needed and no observed impact on the network's TCO over the study period. Assisted driving services, with a slightly higher traffic increment over eMBB services than semi-automated driving of 1.9%, caused network densification in hotspot areas to occur a year earlier than in the eMBB only scenario resulting in a 2.5% increase in costs.

Combining the cost of delivering these new services with their potential to generate new revenue streams shows that there is potential to moderately improve the ROI compared with the baseline eMBB only case and hence de-risk this case further (although not to the same extent as the benefit of multi-tenancy for the cases examined). ROI improvements over the baseline eMBB only single tenant case of 3%, 6%, 7% and 10% were observed for combining eMBB with each of smart meter, assisted driving, infotainment and semi-automated driving respectively.

In our multi-service analysis, we have considered new non-eMBB services that are currently envisaged and that we believe would add most value in our smart city setting. However, as mobile networks continue to evolve and new applications for mobile services continue to emerge there may be more opportunities to increase the value added by multi-service support in mobile networks than that shown here. Further cost reductions in introducing support for services with challenging coverage and reliability requirements may also be possible via virtual network densification made easier via multi-tenancy in 5G NORMA networks as described in Deliverable D3.3 [5GN-D33]. However, given the existing high density of sites in our study area we have not included this effect in our analysis here.

**Key findings regarding the socio-economic case for multi-service networks based on the 5G NORMA proposed architecture**

Our research suggests that the social and wider economic benefits of multi-service mobile networks are substantial. The greatest benefits are likely to come from smart energy, V2I services and increases in productivity related to eMBB and services specific to the verticals, including those falling under Industry 4.0 and others (but not covered in detail in this study). They are of similar orders of magnitude to our revenue forecasts for these services included in our commercial assessment and in some cases, e.g. smart energy, they are substantially higher.

There are several indications as to where intervention may be appropriate, although further research will be necessary, particularly for lower population density areas, to refine this initial research:

- There is a question mark over whether revenues arising from eMBB will continue to be sufficient to cover the cost of infrastructure by itself although the commercial business case is improved by the economies of scope from deploying multi-service networks.
- Although the data volumes involved in smart energy are small compared to other services such as eMBB, it will need nation-wide, reliable coverage. Our business case assessment suggests that there could be material risks to the business case in areas less densely populated than Central London, therefore there is a risk that the market might not be able to provide the necessary coverage on a nation-wide basis. Much depends on how the energy market itself develops and whether microgeneration and electric vehicle charging take off and require dense sensor and actuator networks. We recommend that analysis of the risks to adequate smart grid provision should be incorporated into the strategy for the energy sector and the transition to a low carbon economy.
- V2I services are likely to be commercially viable particularly in the most densely populated cities. However, it is not clear whether the same would be true of the road network outside these areas, particularly given that the quality of mobile coverage on these roads can already vary significantly.

**Key findings regarding implications for stakeholders including MNOs, verticals and regulators of 5G virtualised networks such as 5G NORMA**

The 5G NORMA based architecture enables a new multi-tiered stakeholder model made up of tenants (who acquire mobile services and manage the relationship with end users), mobile service providers (MSPs) (who implement end-to-end network functionality to deliver mobile services) and infrastructure providers (who manage and provider the sites, physical equipment and interconnectivity that MSPs can implement their virtualised network upon).

Given the challenge that the mobile industry faces of flat or declining revenues but growing demand and hence network costs, we have examined how MNOs are already re-positioning themselves within the ecosystem to engage with verticals, provide higher value mobile services and hence generate new and more efficient revenue streams.

We also examine the implications for regulators and governments in ensuring the right regulatory environment is in place to ensure that the social benefits and innovative ecosystems promised by multi-service networks such as those proposed by 5G NORMA are realised.

# Table of Contents

# List of Figures

# List of Tables

# List of Acronyms and Abbreviations

| Term | Description |
|---|---|
| **ARPS** | Average Revenue per Subscriber |
| **B2B** | Business to Business |
| **B2B2C** | Business to Business to Consumer |
| **B2C** | Business to Consumer |
| **CAGR** | Compound Annual Growth Rate |
| **CAPEX** | Capital Expenditure |
| **COTS** | Commercial Off the Shelf |
| **CPRI** | Common Public Radio Interface |
| **C-RAN** | Cloudified Radio Access Network |
| **DCSP** | Data Centre Service Provider |
| **DL** | Downlink |
| **D-RAN** | Distributed Radio Access Network |
| **EBITDA** | Earnings Before Interest, Tax, Depreciation and Amortization |
| **EC** | European Commission |
| **EU** | European Union |
| **eMBB** | Enhanced Mobile Broadband |
| **FDD** | Frequency Division Duplex |
| **FFT** | Fast Fourier Transform |
| **GDP** | Gross Domestic Product |
| **H2020** | Horizon 2020 |
| **HARQ** | Hybrid Automatic Repeat Request |
| **ICT** | Information and Communication Technologies |
| **IoT** | Internet of Things |
| **InP** | Infrastructure Provider |
| **ITS** | Intelligent Transport Systems |
| **LLU** | Local Loop Unbundling |
| **LSA** | Licensed Shared Access |
| **LTE** | Long Term Evolution |
| **MBB** | Mobile Broadband |
| **MCS** | Modulation and Coding Scheme |
| **MIMO** | Multiple Input Multiple Output |
| **MMIMO** | Massive Multiple Input Multiple Output |
| **mMTC** | Massive Machine Type Communications |
| **MNO** | Mobile Network Operator |
| **MOCN** | Multi-Operator Core Network |
| **MORAN** | Multi-Operator Radio Access Network |

| | |
|---|---|
| **MSP** | Mobile Service Provider |
| **MTC** | Machine Type Communications |
| **MU-MIMO** | Multi-user MIMO |
| **MVNO** | Mobile Virtual Network Operator |
| **NaaS** | Network as a Service |
| **NSaaS** | Network Slice as a Service |
| **NFV** | Network Function Virtualisation |
| **NFVI** | Network Function Virtualisation Infrastructure |
| **NORMA** | Novel Radio Multiservice adaptive network Architecture |
| **NPV** | Net Present Value |
| **NR** | New Radio |
| **NSI** | Network Slice Instance |
| **PNF** | Physical Network Function |
| **PPP** | Public Private Partnership |
| **QAM** | Quadrature Amplitude Modulation |
| **QOS** | Quality of Service |
| **QPSK** | Quadrature Phase Shift Keying |
| **RAN** | Radio Access Network |
| **RF** | Radio Frequency |
| **ROI** | Return On Investment |
| **RRH** | Remote Radio Head |
| **SCF** | Small Cell Forum |
| **SDN** | Software Defined Networking |
| **SU-MIMO** | Single user MIMO |
| **TCO** | Total Cost of Ownership |
| **TDD** | Time Division Duplex |
| **TfL** | Transport for London |
| **UL** | Uplink |
| **uMTC** | Ultra-reliable Machine Type Communications |
| **URLLC** | Ultra-Reliable Low Latency Communications |
| **V2I** | Vehicle to Infrastructure communications |
| **V2X** | Vehicle to anything communications |
| **VISP** | Virtualisation Infrastructure Service Provider |
| **VNF** | Virtual Network Function |
| **VNI** | Visual Networking Index |
| **WCDMA** | Wideband Code Division Multiple Access |

# 1 Introduction – 5G's socio-economic promise

## 1.1 Document background and objectives

This is the final report for Work Package 2 (WP2) of the 5G NORMA project. The 5G NORMA project is committed to the design of a virtualised, flexible 5G network architecture that supports network slicing. Key benefits of this architecture approach are:

- Multi-tenancy - the ability to serve multiple service providers from a shared infrastructure set and obtain cost efficiencies via this network sharing approach (i.e. an economies of scale cost benefit).
- Multi-service support - the ability to provide a mix of services with varying quality of service (QoS) requirements, in terms of throughput, reliability and device density, from a single network platform. This can lead to cost efficiencies due to economies of scope (i.e. providing services with different spatial and temporal distributions from a shared infrastructure set) as well as new revenue streams beyond today's business to consumer, enhanced Mobile Broadband (eMBB) service focused mobile networks.

Technical proposals for 5G NORMA and evaluations of key performance indicators on networks performance have already been published in WPs 3, 4 and 5 with key findings and recommendations captured in Deliverable D3.3 [5GN-D33]. D3.3 also expands on the opportunity for 5G NORMA to support a new ecosystem consisting of three key layers of tenants, mobile service providers and infrastructure providers with a range of supplier stakeholders supporting these and opportunities for new entrants and new relationships across these layers.

This document builds on the work in D3.3 by:

- Assessing the commercial case for migration towards virtualised networks as envisaged by 5G NORMA. This includes forecasting the impact on existing enhanced Mobile Broadband (eMBB) revenues and capturing potential new revenue streams from other non-eMBB service categories supported by 5G NORMA. A network dimensioning and cost modelling tool has also been developed in line with the topology and equipment sets required for both today's Distributed Radio Access Networks (D-RAN) and a virtualised 5G NORMA like network architecture, including processing on x86 architecture processors, termed cloudified RAN or C-RAN in this document. This allows corresponding network costs for an example central London deployment scenario to be compared with revenue forecasts to assess the commercial case for migration towards 5G NORMA like networks in a range of "evaluation cases".
- Assessing the potential social benefits brought by 5G NORMA via improvements to existing wireless services and the introduction of new services. The potential role of public private partnerships to unlock these social benefits in cases where the commercial case may be less clear or hold short term risks is also discussed.
- Presenting the new form of ecosystem that 5G NORMA enables and implications for stakeholder groups including:
    - How today's industry players might reposition themselves within this ecosystem to maximise value generation.
    - Implications for new end-users of mobile services and engagement between industry verticals and the mobile industry.
    - Opportunities for new entrants within this new ecosystem.
    - Key aspects raised by flexible, shared, virtualised 5G networks for regulators to consider and considerations on creating the right type of regulatory environment to unlock the significant social benefits promised by future mobile networks.

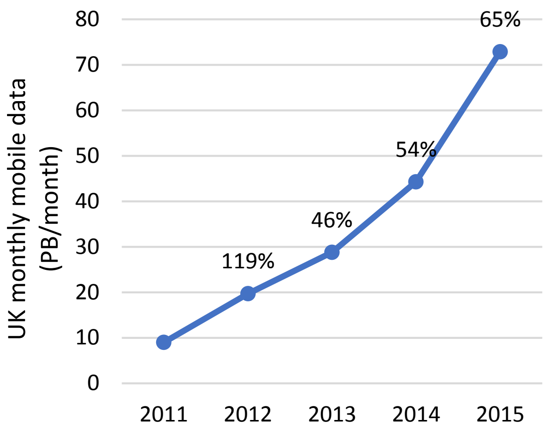
Note our commercial assessment of networks using the 5G NORMA proposed architecture is not meant to give a definitive answer on the business case for such networks as this is subject to the assumptions of our analysis. However, our analysis aims to show likely cost and revenue trends and to expose the issues in future network deployments which may add or reduce risk in the future business case for mobile network services.

Points to note regarding the scope of our commercial analysis, in particular, are:

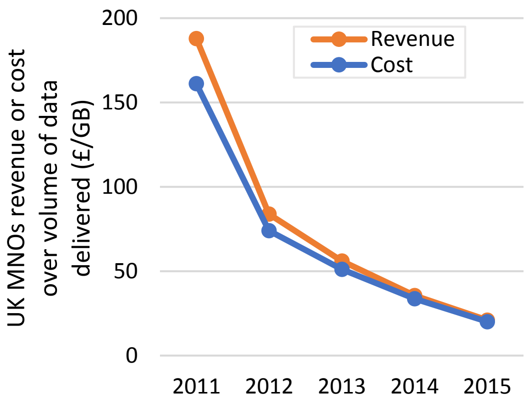
- We focus on a central London study area selected because of its challenging high-density users and range of service requirements. This makes it a prime candidate for migration towards multi-service 5G networks and hence we expect the commercial case to be most positive here. Our conclusions cannot be directly applied beyond smart city scenarios without further work. Our conclusions also assume a particular migration strategy for a typical Mobile Network Operator (MNO) and the benefits identified will be shaped by the specific situation and approach taken by each MNO in practice.
- As the focus of 5G NORMA is on developing a new flexible 5G network architecture, the focus of our assessment here is on the benefits delivered by proposed architectural innovations (most notably multi-tenancy and multi-service support via network slicing). We do not distinguish between the air interface capabilities of 4G and 5G and assume the same spectrum bands, bandwidths, antenna configurations and usage of small cells across all architecture options assessed. Our conclusions are therefore applicable if a network using an LTE-A air interface was virtualised and migrated towards a 5G NORMA like C-RAN architecture and do not rely on usage of 5G New Radio (NR).
- Our modelling of RAN costs assumes that processing equipment within the network is driven mainly by user plane traffic. We do not directly model the impact of control plane traffic, the core network or management and orchestration functions on equipment volumes. However, in our commercial assessment an uplift of 10% is applied to RAN costs to allow for these items plus an additional 30% for administrative costs. As such we do not directly model the details of every technique proposed by the other Work Packages but rather the benefit of the key 5G NORMA innovations of multi-tenancy and multi-service (which the techniques developed by the Work Packages enable and support) and migration towards these.
- We do not fully cover 5G NR aspects like the radio protocol stack, Central/Distributed Unit (CU/DU) separation with High/Low Layer Split (HLS/LLS) features (and subsequent impact on transport data rates). Instead we took the 4G LTE protocol stack as a basis for evaluation (with the exception of extension to higher antenna port numbers) as the details of the 5G NR specification were still being debated in 3GPP during the lifetime of this study.
- All cost assumptions included in our analysis are based on a mixture of public sources and industry knowledge interpreted in the context of virtualised networks in a 2020 to 2030 timeframe. They are not values explicitly provided by vendors or operators within the consortium.

## 1.2 Pressures in today's mobile industry – revenue and cost trends

While the annual growth rate of mobile demand in more developed economies has slowed over recent years it is still significant. Figure 1-1 (a), for example, shows mobile data growth trends for the UK. Rather than being driven by growing subscriber volumes, these increasing traffic volumes are being driven by high user expectations of wireless services with growing demand for high quality video services in both uplink (UL) and downlink (DL) set to drive future demand growth [Eri16].




(a) UK monthly mobile data volume. Annotations report year on year percentage increase trends. Source: [Ofc16]




(b) UK MNO revenue vs. costs per GB trends based on UK traffic volumes from [Ofc16] and revenue and spend reported by [Ana16]

**Figure 1-1: UK data, cost and revenue trends**

However, alongside these growing traffic volumes and more demanding user expectations, revenues per subscriber are declining. Ofcom, for example, estimates that there was a 10% drop in real terms in the retail revenue per subscriber for UK Mobile Network Operators (MNOs) between 2011 and 2016 [Ofc17]. This decline is also reflected by total revenues reported for MNOs over this period [Ana16].

Reported MNO costs, rather than declining, appear that they are being maintained at similar levels over the past 5 years [Ana16]. Combining these reported revenues, costs and traffic trends for the UK mobile industry gives the revenue vs. cost per Gigabyte (GB) of data delivered trend, which is shown in Figure 1-1 (b). This shows a trend of the gap between revenue and cost per GB delivered narrowing over time to what would appear to be an unsustainable level.

## 1.3 The promise of 5G NORMA

5G NORMA has developed a virtualised, flexible 5G network architecture that supports network slicing[2]. This promises to create a viable platform to help reduce the cost per GB of data delivered via multi-tenancy (economies of scale) and multi-service (economies of scope) support. Crucially, it also provides routes to disruptive business models and potential new revenue streams via multi-service support.

In this report, we investigate the commercial viability of the 5G NORMA architecture from the following perspectives:

- Is there a cost penalty of 5G virtualised networks vs. today’s non-virtualised RANs with distributed infrastructure?
- How can multi-tenancy and network sharing enabled via network slicing reduce network costs per GB of data delivered?
- What additional revenue streams can multi-service support via network slicing provide and what impact does this have on revenue per GB trends for MNOs and other service providers?

We acknowledge that some industry commentators have questioned the value of 5G.

- Webb has indicated [Web16] that:

[2] Network slices are formed in virtualised networks by implementing chains of Network Functions (NFs) related to one or more services across a shared common infrastructure set.

  - The 5G vision is too utopian requiring huge – mainly unachievable – advances in wireless technology.
  - Currently achievable speeds are adequate for all foreseeable uses – what is missing is reliable connectivity everywhere and Wi-Fi is a key component of the solution.
  - The costs of deploying 5G will be too high and there are no clear benefits for operators.
  - Regulatory focus on competition undermines the ability of operators to finance 5G.
  - Significant structural change is needed in the industry – from masts and antennas (M&A) down to RAN sharing.
  - A different 5G vision is needed – supporting Internet of Things (IoT) and consistent MBB to establish a "vision as espoused by METIS[3]".
- Geoff Varrall has opined [Vir17] that 5G must:
  - Deliver cost and power improvements for Mobile Broadband (MBB) and Internet of Things (IoT).
  - Provide improved operator earnings before interest, tax, depreciation and amortisation (EBITDA).
  - Support a range of average revenue per subscriber (ARPS) across developed and less well-developed economies.
  - Provide wide area coverage for IoT whilst delivering MBB in dense environments.

In this report, we aim to address some of the above concerns by:

- Building our revenue and cost forecasts based on service descriptions that are relatively modest compared with other 5G projects given that many air interface techniques proposed for 5G could, arguably, be applied to 4G networks. Instead we focus on the benefits delivered by 5G NORMA from an architectural perspective.
- Reviewing potential changes in the mobile industry ecosystem required to get the most benefit from 5G networks, highlighting key barriers in achieving these changes and the consequences and key considerations for different stakeholder groups.

## 1.4 The new stakeholder model of 5G NORMA

In today's cellular networks the mobile network operator (MNO) tends to own the spectrum, antenna sites and core network sites inclusive of corresponding equipment. They also implement the required functionality at each site to deliver the required service level to either their subscribers and/or a mobile virtual network operator (MVNO). Dependent on his status the MNO may also own the inter-site transport network (integrated operator) or be leasing the corresponding lines from another operator.

Within 5G virtualised networks as proposed by 5G-NORMA there is the opportunity to move away from this highly integrated stakeholder model to one with more layers of stakeholders. These extra layers of stakeholders introduce opportunities for new entrants to work with existing ones to provide customised equipment or service implementation wherever and whenever needed. This ability to customise will ideally lead to the integration of new verticals into the mobile ecosystem, opportunities for new revenues streams for mobile service providers, and knock-on

[3] Where METIS was a European Commission funded Framework 7 research project with the objective to lay the foundation for a future mobile and wireless communications system for 2020 and beyond. See [MET14-D66] for further details.

benefits to society more generally. One view of the tiered stakeholder model, which is enabled through a flexible 5G network is shown in Figure 1-2.

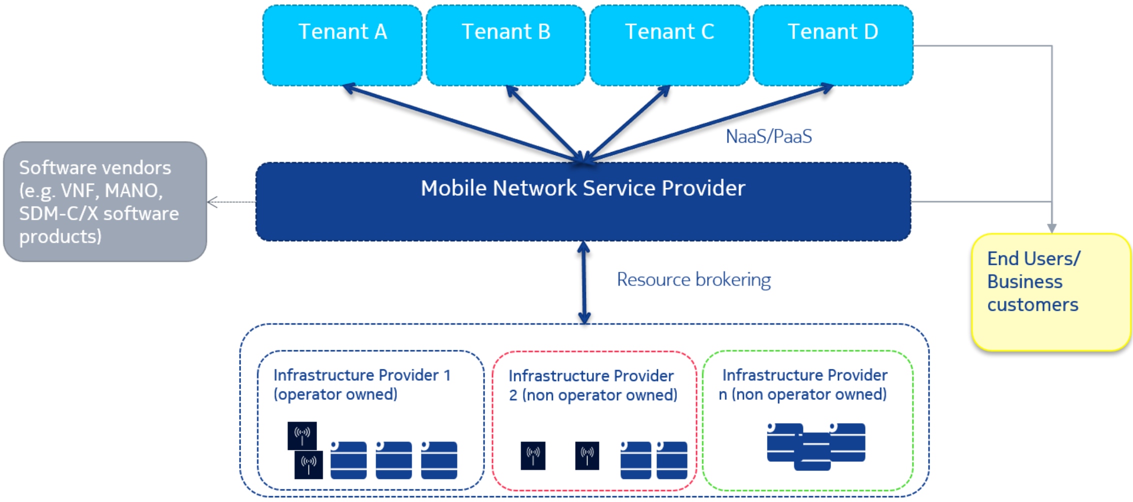



**Figure 1-2: Relationship between stakeholders in 5G NORMA with Mobile Service Provider in the core place [5GN-D32]**

The key stakeholder roles proposed within this and referred to throughout this document include:

- **Mobile Service Provider (MSP),** provides mobile internet connectivity and telecommunication services to either end-users directly, i.e., through a business-to-customer (B2C) relationship, or via an intermediate “tenant”, i.e., a business-to-business (B2B) or business-to-business-to-anyone (B2B2X) relationship; see next stakeholder description. The dedicated logical mobile network resources offered by an MSP are based on Network Slice Instances (NSIs) realising the relevant NF chains to support the instantiated telecommunication services, e.g., eMBB or mMTC. In case of intermediate tenants, the MSP’s offerings are Network (Slice) as a Service (N(S)aaS) or Platform as a Service (PaaS). An MSP is responsible for design, build and operation of its service offerings.
- **Tenant**, usually a business entity, buys and leverages a 5G-NORMA network slice and services provided by the MSP. A tenant can, for example, be an MVNO, an enterprise (e.g., from a vertical industry) or other organisations that require telecommunications services for their internal business operations or for offers to their customers.
- **Infrastructure Provider (InP)** is the entity/company that owns and manages parts of or all of the infrastructure of the network under consideration and offers it to the MSP, i.e., Infrastructure as a Service (IaaS). The InP role may be further sub-divided into antenna site infrastructure provider, transport network provider, and data centre service provider (DCSP). The former owns the physical infrastructure such as the antenna sites, the HW equipment for the antennas and Remote Radio Heads (RRHs), monolithic base stations, etc. (i.e., infrastructure related to PNFs). The latter is represented by the collapsed roles of an entity/company that owns and manages local and/or central data centres.

Within this 5G NORMA stakeholder model, a Mobile Network Operator (MNO) is an entity that operates and owns the mobile network, i.e., it vertically integrates the roles of MSP and InP into a single stakeholder entity.

In practice, there may be also a so-called **Virtualisation Infrastructure Service Provider (VISP)** which designs, builds and operates its virtualisation infrastructure(s) on top of InP services provided by one or more DCSPs. The VISP offers its infrastructure service to the MSP.

Further roles in the stakeholder model to be mentioned are the **HW supplier** offering HW to the InPs (server, antenna, cable, …), the **NFV Infrastructure (NFVI) supplier** providing the corresponding NFV infrastructure to its customers, i.e. to the VISP and/or directly to the MSP, respectively, and finally the **VNF supplier** offering virtualised SW components to the MSP.

## 1.5 The social and wider economic benefits of wireless services

As well as commercial benefits, 5G promises to play an important role in delivering key social and environmental goals by enabling mobile networks to support new types of services to a wider range of users than previously. This leads to a classic problem of whether and how government should intervene to help realise social value from new services where the business case might not yet be clear or the short-term return on investment may be risky. Additionally, the right regulatory environment will be required to fully unlock these potential benefits.

In this report, we aim to quantify not only revenue opportunities from new 5G services but also the social and economic impact these may have. We review circumstances where public private partnership might be beneficial to ensure that these social benefits are realised. We also review actions already taken by regulators across different countries and how these have impacted the regulatory environment and migration towards multi-tenant, multi-service mobile networks.

## 1.6 Structure of the document

This document is structured around the two key discussion threads of:

- The commercial case for 5G NORMA
    - Chapter 2 presents our methodology and assumptions in building up the commercial case for 5G NORMA. In particular, it introduces the three evaluation cases that are core to our cost analysis and key assumptions in our cost modelling.
    - Chapter 3 presents results from our cost modelling of a 5G NORMA network in a central London scenario for each of the three evaluation cases introduced in Chapter 2. A sensitivity analysis is presented also for each evaluation case.
    - Chapter 4 presents the forecast of 5G NORMA revenues across a range of services as envisaged for our central London smart city scenario. These are then combined with the costs from Chapter 3 to assess the commercial viability of 5G NORMA.
- The social and economic benefits of 5G NORMA
    - Chapter 5 presents the social and wider economic consequences of the new range of wireless services that could be delivered by 5G NORMA. It also discusses the link between creating the right political and regulatory environment to enable industry to be better placed to develop and deliver networks that unlock these wider social and economic benefits.

Chapter 6 then combines the findings of the commercial and social benefits assessment of 5G NORMA and presents the revised ecosystem envisaged under 5G NORMA like networks. Examples of migration towards this ecosystem already evident today are reported before presenting the consequences for the different stakeholder groups of verticals, MNOs and regulators. Finally, Chapter 7 presents conclusions out of the work performed in WP2 of 5G NORMA.

Additionally, the following appendices are included:

- Appendix A provides the performance, coverage and capacity requirements of services beyond eMBB considered for our multi-service Evaluation Case 3.
- Appendix B provides further details on the mobile traffic forecasts for a range of services used for our analysis.
- Appendix C provides further details on the set up and assumptions of the network dimensioning and cost modelling tool developed and used as part of our analysis.

# 2 Business case evaluation methodology and assumptions – evaluation cases, traffic profiles and network dimensioning

This section briefly introduces our methodology and key assumptions for assessing the commercial benefits of 5G NORMA.

## 2.1 Methodology for building a commercial business case of 5G NORMA

Figure 2-1 gives an overview of the process applied to assessing the commercial feasibility of 5G NORMA. Several 5G evaluation cases are defined which are discussed further in Section 2.2. These describe the potential set of services to be delivered and different network deployment approaches to be compared. For each of the three 5G evaluation cases we define the expected traffic profile for the services being considered over the timeframe from 2020 to 2030. Given that growth in data demand is uncertain we have developed low, medium and high traffic forecasts. A network dimensioning exercise is performed in our central London study area for each of these three evaluation cases to give a range of network evolution possibilities and hence network costs between 2020 and 2030. This range of network costs can then be compared against the corresponding range of revenues to assess the commercial viability of 5G NORMA.

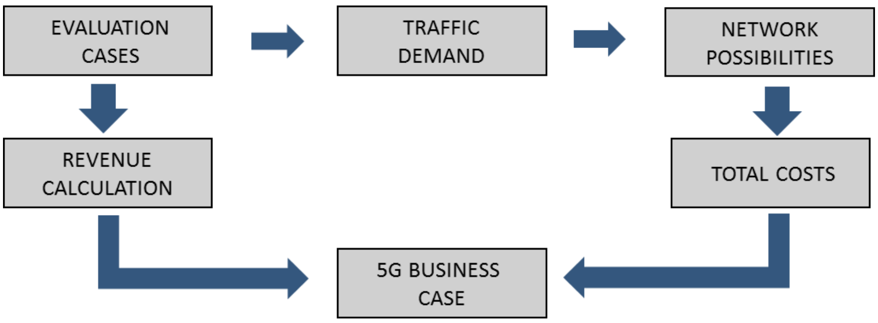



**Figure 2-1: High level approach to the commercial assessment of 5G NORMA**

Note that in our cost modelling we only model costs of the RAN and specifically the antenna[4] and edge cloud[5] sites. We do not explicitly model in our network dimensioning and costs tool the costs of the core network, spectrum or overhead costs such as administrative and retail costs. Instead core network costs are estimated to be approximately an additional 10% compared with modelled RAN costs based on discussions with consortium partners. Further research is needed to determine any additional costs to support the orchestrators and other additional network control elements required to support the 5G NORMA proposed architecture but it is not thought that this would increase this 10% additional cost for core network costs greatly. Administrative and retail costs are estimated at 30% of the total cost of sales and also included in our commercial assessment in Section 4.

[4] Radio site containing as a minimum the antennas and potentially some radio protocol stack processing.

[5] Small, locally located data centres with processing capacity close to the antenna site where some virtualised network functions may be implemented.

## 2.2 Recap of 5G NORMA evaluation cases

For the commercial assessment of 5G NORMA we assume the same physical deployment scenario of central London as considered for technical evaluations in Deliverable D3.3 [5GN-D33], see Figure 2-2. This study area is defined as the union of the following three central London boroughs which makes up an area of 37.56 $km^2$:

- Kensington and Chelsea
- City of Westminster
- City and County of the City of London

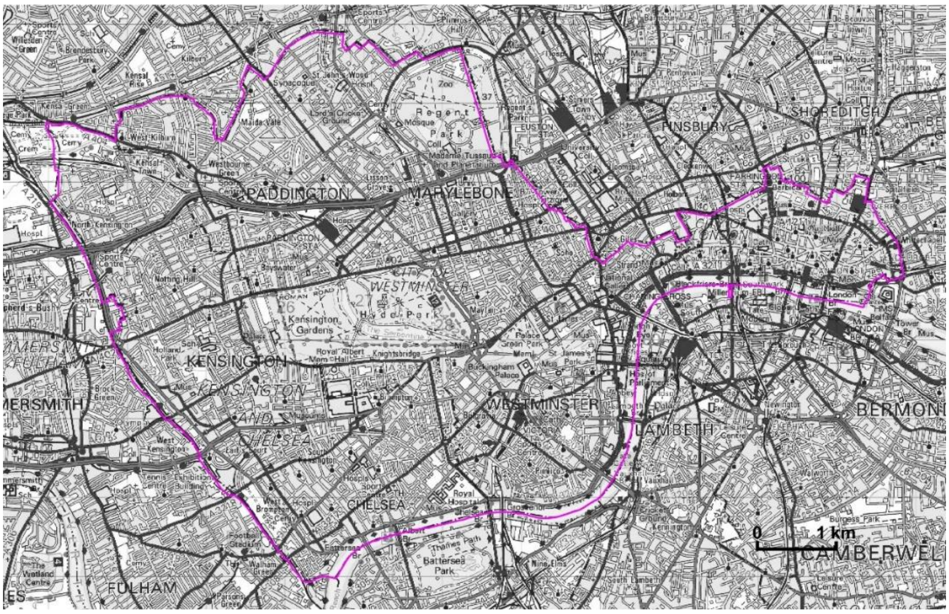



**Figure 2-2: Study area in central London being focused on for 5G NORMA technical and economic evaluations**

This is a representatively busy European metropolitan location having a very high and growing population density that is likely to be able to demonstrate features that can highlight 5G NORMA benefits such as:

- Fast uptake in technology and devices
- New technology greatly benefitting the economy, reducing carbon emissions and overall efficiency
- Planned infrastructure upgrades as population grows

As highlighted by D3.3, the migration to 5G NORMA like networks will not be a sudden transition but will happen in small targeted areas initially where the business case makes sense and gradually expand from these initial deployments. This central London location is considered a good candidate location for early 5G deployment given:

- The potential requirement for a wide range of non-eMBB wireless services ranging from vehicle to infrastructure (V2I) to smart metering applications.
- Having a high existing availability of dark fibre and fixed telecom exchanges which could be used as potential edge cloud site locations to support virtualised network deployments.

In line with D3.3, our commercial assessment of 5G NORMA focuses on three evaluation cases as follows:

- Evaluation Case 1 – C-RAN vs. D-RAN evaluation case
- Evaluation Case 2 – Multi-tenant evaluation case
- Evaluation Case 3 – Multi-service evaluation case

Evaluation Case 1 considers a single eMBB only MSP with a typical 18% market share whereas Evaluation Case 2 considers two such MSPs. Evaluation Case 3 considers a single eMBB MSP but where this MSP also provides V2I and smart metering services with a 100% market share assumed in for these additional services within the study area.

### 2.2.1 Evaluation Case 1 – C-RAN vs. D-RAN comparison

The network architecture proposed by 5G NORMA is based on a flexible and programmable, highly virtualised network infrastructure where so-called network slices [5GN-D33] can be readily formed to meet the specific requirements of a given service or target market.

Network slices are formed by implementing chains of Network Functions (NFs) related to one or more services across a shared common infrastructure set. The underlying infrastructure layer may span across antenna sites (which is the radio site containing as a minimum the antennas and potentially some radio protocol stack processing), edge cloud sites (small, locally located data centres with processing capacity close to the antenna site) and central cloud locations (centrally located data centres hosting a significantly large collection of processing, storage and networking) as shown by site chain configuration 2 in Figure 2-3. If required network slice provisioning may span across different Infrastructure Provider (InP) domains to allow wider service coverage.

Evaluation Case 1 assesses the cost penalty of delivering eMBB services via a 5G NORMA like cloudified network (C-RAN), as described above, compared against today’s D-RAN infrastructure. It considers the network evolution required by a single Mobile Service Provider (MSP) in meeting growing eMBB demand from consumer portable devices over the time period 2020 to 2030. It is assumed that the MSP owns and runs its own network infrastructure sites and equipment set. While different radio protocol splits can be applied in 5G NORMA networks, we investigate the most extreme case where the only equipment at the antenna site (except the antenna itself) is a remote radio head (RRH). This RRH is formed of the RF front end with a Common Public Radio Interface (CPRI) [Cpr15] connection via dark fibre to an intermediate, local edge cloud site where the baseband processing and remainder of the radio protocol stack will be carried out on Commercial Off the Shelf (COTS) x86 architecture processors (see Appendix C for virtualisation dimensioning assumptions).

The different site and equipment elements assumed for C-RAN and D-RAN under this evaluation case are illustrated in Figure 2-3 (and aligned with site chain configurations 1 and 2 as introduced in our earlier Deliverable D2.2 [5GN-D22]). The cost model used in our analysis (see Section 2.4) dimensions equipment based on user plane traffic requirements which are assumed to dominate the processing requirements of the network. The cost model and analysis presented in Section 3.1 does not directly consider control plane requirements, core network functions and network management and orchestrator functions although some allowance is made for some of these in translating RAN costs from the cost model to operating costs in our commercial assessment (see Section 4).

Note that for the most challenging macrocell antenna site configuration of antennas, spectrum bands and bandwidths considered in our analysis (see Section 2.4.3) a CPRI line rate of approximately 80 Gbit/s would be required. This would imply a fibre rate of 300 Gbit/s. Whilst this is within the capabilities of today’s fibre products if a star topology is used (as we have modelled), issues such as synchronization, price, availability and reliability within required cost targets stretch feasibility. With ring fibre topologies feasibility is questionable. However, we note that the split analysis (including interface names, e.g. S1) in Figure 2-3 is based on the LTE stack/architecture, as the NR/ Next Generation Radio Access Network definition was not matured enough at the point in time that this study was performed. With novel approaches like eCPRI (applying a split within the PHY layer, i.e. Option 7 in 3GPP) a distinct reduction, claimed to be in the order of 10 times over standard CPRI, of the required throughput can be achieved on the interface compared to CPRI (Option 8) [Cpr17].

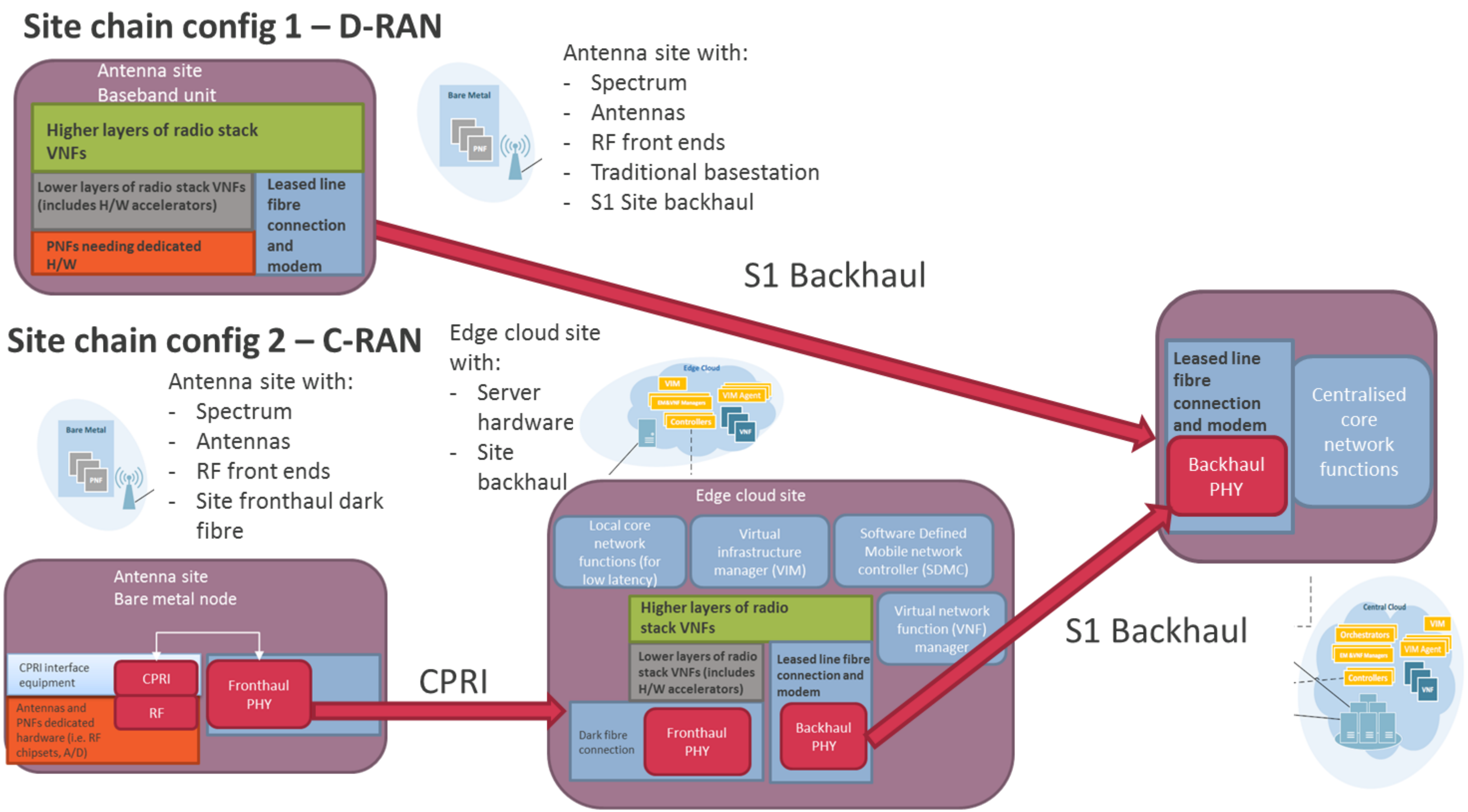



**Figure 2-3: Overview of the site and equipment elements assumed between D-RAN and C-RAN in Evaluation Case 1**

While there will be slightly different equipment required at the macrocell antenna site RRH to apply an eCPRI rather than CPRI interface, the cost of components at the resolution of the model required for the evaluation presented in this report is comparable between CPRI and eCPRI. Therefore, the viability for the links dimensioned for in this study is validated.

The C-RAN configuration is only applied to macrocells. Small cells are also considered in the network evolution, but we assume that these remain as D-RAN sites in both cases. Although there have been some examples of C-RAN small cells being trialed already, today's small cell deployments, due to the density of sites, tend to make heavy use of wireless backhaul and so might not lend themselves so readily to the level of virtualisation considered here with a CPRI connection via dark fibre being very costly to install to all sites (noting that this of course depends strongly on the existing MNO infrastructure and fibre topology in use). For 5G deployment there is also the issue that some small cells will be mmWave small cells (applying Massive MIMO) which would require extremely high throughputs in the case of CPRI-like interfaces (noting the comment regarding eCPRI earlier).

Overall, Evaluation Case 1 aims to understand any potential cost penalty arising from 5G NORMA like C-RAN networks compared with today's D-RAN networks. The key trade-offs investigated include:

- Any cost benefits from aggregating processing at an edge cloud site on COTS equipment rather than across multiple antenna sites.
- The additional cost of setting up and running edge cloud sites in the C-RAN configuration and whether this outweighs the proposed above benefit.
- The cost implications of requiring dark fibre transport to C-RAN antenna sites compared with the potential for less costly site transport options with D-RAN.

### 2.2.2 Evaluation Case 2 – multi-tenant eMBB scenario

The 5G NORMA network architecture supports multi-tenancy. Within the context of 5G the MSP provides the end-to-end connectivity and network functionality to support the mobile services requested by multiple tenants with their individual service requirements. The MSP accomplishes this by using sites, equipment and inter-site connectivity provided by one or more InPs. In single tenant networks a given infrastructure set is used by only one MSP to deliver services to their own end users and the roles of tenant (managing the relationship with the end use), MSP (implementing the end-to-end network functionality to deliver services to a given service level agreement) and InP (running the sites, equipment and site interconnects) become combined. However, in multi-tenant networks the same infrastructure set can be used by the MSP for more than one tenant to implement the end-to-end network functionality required to support the services being provided by each tenant to their own groups of end users in their individual network slices. Additionally, network slicing in multi-tenant networks may also support multiple MSPs sharing the same infrastructure set but implementing their own network functions as shown in Figure 2-4 (which might be more appropriate for two MNOs sharing infrastructure but wanting to maintain control on their network implementation).

Passive network sharing whereby mobile network operators share site locations, towers/structures at these locations, antennas and site facilities like backhaul and power already exists today. Active network sharing where active network equipment as well as sites, structures and antennas are shared are also possible through Multi-Operator RAN (MORAN) and Multi-Operator Core Networks (MOCN). These active sharing techniques have been standardised in 3GPP [23.251] with MORAN requiring dedicated carriers between sharing operators while MOCN includes spectrum sharing. A few options of network sharing are described in [Gsm12] and [Wik16]. However, multi-tenancy in 5G NORMA networks takes this sharing to another level with infrastructure, equipment, inter-site connectivity and spectrum potentially being used to flexibly provide, at a much more granular level than currently, the processing, storage and connectivity for a mobile service provider (MSP) to implement end-to-end mobile services or "network slices" for multiple tenants each delivering their own target services over the network [Ngm16 and

RSA+16]. The key disadvantages to active network sharing in current cellular networks is that settings of the shared sites must be a compromise between the different parties sharing. In a multi-tenant 5G network the virtualisation of network functions and partitioning of these between network slices means each party can control how their service is delivered via the network resource available and hence have better control over user experience.

Evaluation Case 2 assesses the value of multi-tenancy or the sharing of network infrastructure and equipment in an eMBB only scenario. Here we consider the cost of two MSPs based on their network evolution from 2020 to 2030 when they own and manage separate infrastructure sets (non-sharing case in Figure 2-4). We then compare network costs when the combined demand of both MSPs is delivered via a single shared infrastructure set made up of a combination of both operators' existing site portfolios in 2020 which evolves to meet demand out to 2030 (shared case in Figure 2-4). Each site in this shared infrastructure set is assumed to have access to a shared spectrum set or pool of the spectrum held by each MSP i.e. spectrum is shared as well as infrastructure. In both cases we assume a virtualised C-RAN 5G NORMA like network to assess the value of multi-tenancy in 5G NORMA beyond the baseline case. This sharing of infrastructure amongst existing MNOs could be realized as a single new MSP created to implement the virtual network functions required per service and provide services to the existing MNOs and their users who become tenants of the MSP. If the MNO would like to maintain more control over their network implementation it is alternatively possible to realise two MSPs using the same shared infrastructure set. Similarly, the shared infrastructure set could be maintained by a new joint entity infrastructure provider who would provide the Network As a Service (NaaS) and charge MSPs by apportioning costs in line with utilisation of network resources by traffic from the different parties. Revenue would still be received by the MSPs and their tenants as per pre-sharing and not be impacted by the sharing arrangement.

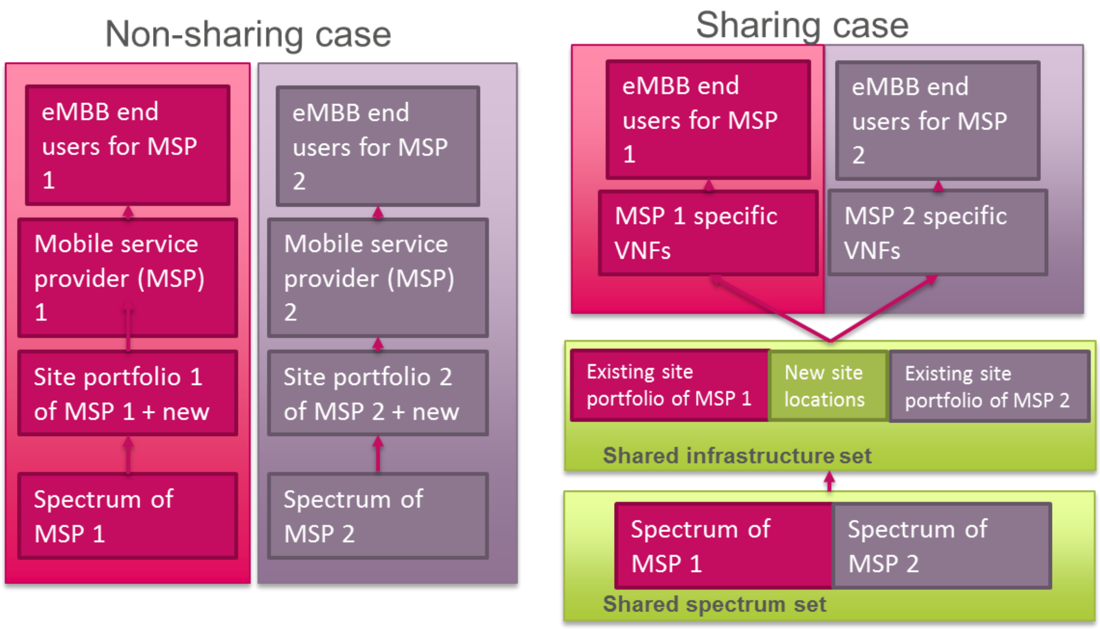



**Figure 2-4: Non-shared vs. shared use cases in Evaluation Case 2**

As in Evaluation Case 1, we assume that small cells are not virtualised to maintain consistency across the cases. Therefore, small cells in this case are not assumed to be shared under the multi-tenant case and spectrum bands from small cells are not considered as part of the shared spectrum set between the two MSPs.

### 2.2.3 Evaluation Case 3 – multi-service scenario

This case assesses the value of multi-service support in 5G NORMA and introduces services beyond eMBB to the baseline single MSP C-RAN network considered in Evaluation Case 1 as expected in a smart city deployment. It examines a full range of services covering high throughput (eMBB), high device densities but small packet sizes (massive machine type communications aka MTC) and high reliability (ultra-reliable machine type communications aka uMTC). The services focused on have been selected based on:

- Being applicable to the central London study area.
- Showing promise for generating significant incremental revenues and social benefits.

Services evaluated include:

- eMBB for consumer portable devices (such as smartphones, tablets and laptops)
  - Driven by live streaming of video with up to 4K pixels of resolution
- Vehicle to Infrastructure (V2I)
  - Infotainment and advertising to passengers
  - Assisted driving (made up of information services on road and driving conditions and navigation)
  - Semi-automated driving services
- Smart cities
  - Environmental monitoring, Intelligent Transport Systems (ITS) and waste management sensors
  - Smart metering and smart grids
- Logistics
  - Sensor data for tracking goods in transit

These services map to the three broad service categories of eMBB, mMTC and uMTC as shown in Table 2-1. Performance, capacity and coverage requirements are given in [5GN-D33] and reproduced in Appendix A for ease of reference.

**Table 2-1: Categorisation of example services to service classes**

| | eMBB for consumer portable devices | Vehicle to infrastructure | | | Smart cities | | Logistics |
|---|---|---|---|---|---|---|---|
| | **Enhanced video streaming – Up to 4K resolution** | **Info-tainment** | **Assisted driving** | **Semi-automated driving** | **Environ-mental monitors, Intelligent Transport Systems (ITS) and waste management** | **Smart energy** | **Tracking goods** |
| **eMBB** | X | X | | | | | |
| **mMTC** | | | X | | X | X | X |
| **uMTC** | | | | X | | | |

We note that the 3GPP standards for today's LTE networks continue to evolve so that services such as those considered here might also be delivered via LTE-A platforms. However, similar to the multi-tenancy case, the ability to support network slicing in 5G NORMA presents an opportunity for more granularity and control over how a service is delivered and ensuring its quality level to stakeholders beyond solely the MNO. This may be key in engaging with verticals with specific requirements which prevent use of public mobile networks today. This may for example be because of security concerns which can potentially be overcome by network slices in 5G NORMA as discussed for an Industry 4.0 example already in D3.3 [5GN-D33]. Additionally, network slicing in 5G NORMA presents the opportunity to rapidly roll out and try new services and business relationships without significant investment for each new service added and hence reduced risk. The ability to instantiate VNFs in a matter of seconds has been demonstrated in WP6 of 5G NORMA.

In our commercial assessment of multi-service, we make the following assumptions regarding market share:

- For eMBB to consumer portable devices we assume market share per MSP in line with the market share of a typical UK MNO (of 18%).
- For smart city services, we assume that the city council would award provision of these services to a single MSP particularly within the limitations of the study area. Therefore a 100% market share is assumed.
- For V2I services the market evolution is less clear than in the above two cases (i.e. would each vehicle manufacturer acquire services from different MSPs or would MSPs share infrastructure and revenues to provide a single V2I service platform across all vehicle manufacturers?). We assume in the limitations of the study area that these services will be provided by a single MSP i.e. a 100% market share. This may be optimistic but have made this simplified assumption in the absence of a strong rationale towards other market shares. Note our analysis is not intended to be a definitive answer on the V2I business case but to assess the factors that impact the V2I commercial case. Additionally, for high reliability services like semi-automated driving some network repurposing to accommodate the higher reliability requirement may be needed which may be done more efficiently via virtual basestation densification i.e. sharing of infrastructure amongst MSPs. In this case MSPs might share revenues but additional infrastructure costs would also be shared.

Note that market share assumptions impact both revenue (via subscriber volumes) but also costs (via traffic levels to be served).

## 2.3 Traffic profiles considered

### 2.3.1 eMBB for consumer portable devices baseline case

The medium traffic forecast or baseline volume of eMBB traffic to be served by mobile networks in the study area across all 3 evaluation cases is taken from Cisco's Visual Networking Index (VNI) [Cis16] as follows:

- For 2017 to 2020, the Cisco VNI mobile traffic volumes forecast is used directly (with an average traffic volume growth of 48% Compound Annual Growth Rate (CAGR) over the 5 year period provided of 2015 to 2020) to dimension the starting network at 2020 (see Section 2.4 for network dimensioning rules).
- Beyond 2020, growth of 30% CAGR is used in line with D3.2 [5GN-D32] and the trend of a reducing growth CAGR over time observed from the Cisco VNI traffic volumes given up to 2020.

This gives the eMBB traffic forecast per head of population per month for the UK as shown in Figure 2-5.

As described in Appendix B, this is translated to an outdoor busy hour eMBB traffic density for the study area by allowing for:

- The residential population density of the study area
- An uplift on the above population to allow for commuters
- The expected temporal distribution of outdoor demand over different times of the day

Based on input from partners in the 5G NORMA consortium, we assume a cell is at maximum capacity, and either need to be upgraded or a new site built to accommodate more demand, once the average busy hour physical resource block (PRB) utilisation reaches 65% to allow for peaks in demand within the busy hour traffic levels and to limit interference between cells.

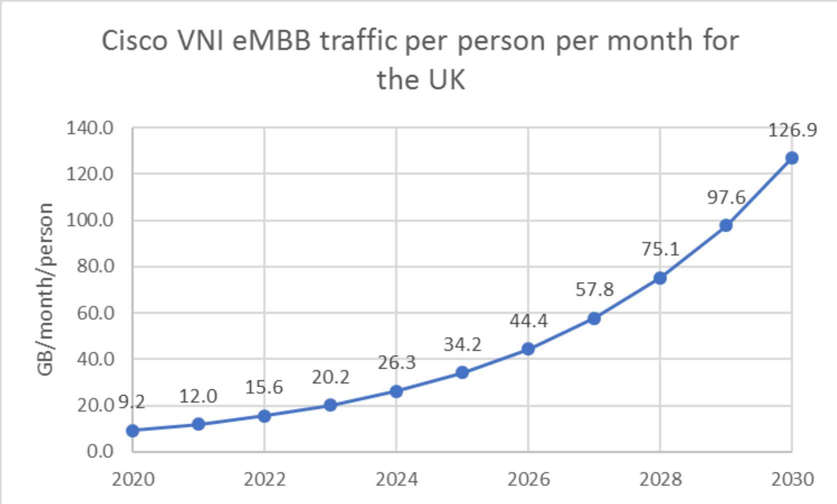



**Figure 2-5: eMBB traffic forecast per head of population for the UK per month based on Cisco VNI**

### 2.3.2 Demand profiles for non-eMBB services

Additional to eMBB traffic, we forecast the traffic volume for a number of non- eMBB services as required for Evaluation Case 3. A bottom up approach to forecasting demand for these services has been applied in the absence of existing traffic forecasts for these services for the UK.

Key assumptions in these demand forecasts for non eMBB services are given here with further details in Appendix B.

**Table 2-2: V2I traffic forecast key assumptions**

| | Infotainment | Assisted driving | Semi-automated driving |
|---|---|---|---|
| **Typical data rates and packet sizes** | Assume up to 3 simultaneous 4K video streams required to a vehicle:<br>Peak rates of 75 Mbit/s Downlink (DL)<br>Cell edge rates of 10 Mbit/s (DL) | Up to 6 kB packets<br>0.5 Mbit/s (DL)<br>0.5 Mbit/s (UL) | Up to 6 kB packets<br>0.5 Mbit/s (DL)<br>0.5 Mbit/s Uplink (UL) |
| **Average demand per vehicle** | On average 1 GB per day per vehicle of infotainment traffic consumed in 2020 growing to 25 GB per day per car by 2030 i.e. approx. 40% CAGR from 2020 to 2030. | On average 52 MB consumed per day per vehicle in study area in 2020 growing to 1711 MB per day per car in 2030 i.e. 42% CAGR. | On average 52 MB consumed per day per vehicle in study area in 2021 growing to 1503 MB per day per car in 2030 i.e. 45% CAGR. Note 0% uptake in 2020 so on average 0 demand per car for this service. |
| **Density of vehicles in the study area** | On average 325 active vehicles on roads per km$^2$ | On average 325 active vehicles on roads per km$^2$ | On average 325 active vehicles on roads per km$^2$ |

**Table 2-3: Traffic forecast key assumptions for smart city devices**

| | Environmental monitors, waste management and congestion control | Smart meters | Smart grid |
|---|---|---|---|
| **Typical data rates and packet sizes** | Minimal data rates<br>Typically, 1 B packets<br>1-2 packets transferred per minute | Minimal data rates<br>Typically, 200 B messages<br>8 messages transferred per day | 20 B command messages<br>10 commands sent per day per smart meter device |
| **Average demand per device** | On average 229 B per day per roadside item (i.e. traffic lights, road signs, bins etc.) in 2020 growing to 1516 B per day per roadside item by 2030. This is a CAGR of 21%. | 1600 B per smart meter per day from 2020 to 2030. | 60,000 B per smart grid neighbour area network (NAN) [6]gateway |
| **Density of devices in the study area** | 50 per km$^2$ (based on traffic signals and roadsigns alone)<br>Assume sensors in bins and environmental monitors might double this density of sensors to 100 per km$^2$ | Approx. 30,000 per km$^2$ in central London | 1.3 smart grid neighbour area network gateways per km$^2$ in 2020 growing to 25.6 per km$^2$ by 2030 |

**Table 2-4: Logistics key traffic assumptions**

| | Logistics |
|---|---|
| **Typical data rates and packet sizes** | Minimal data rates<br>Typically 200 B messages<br>100 messages transferred per day (i.e. updates every 15 minutes)<br>Assume 200 tracked items per goods vehicle |
| **Average demand per vehicle** | On average 4 MB per day per equipped vehicle |
| **Density of vehicles in the study area** | On average 9 smart logistics vehicles per km$^2$ in 2020 growing to 58 by 2030 i.e. a 21% CAGR. |

Combining these traffic forecasts for non-eMBB services with our existing eMBB baseline services gives the medium traffic growth forecast as shown in Figure 2-6 for the study area. Notably, eMBB traffic to consumer portable devices very much dominates the traffic volumes.

[6] Where a NAN is an aggregation point for collecting information from a few hundred smart meters and relaying this to a central controller [CSB+16].

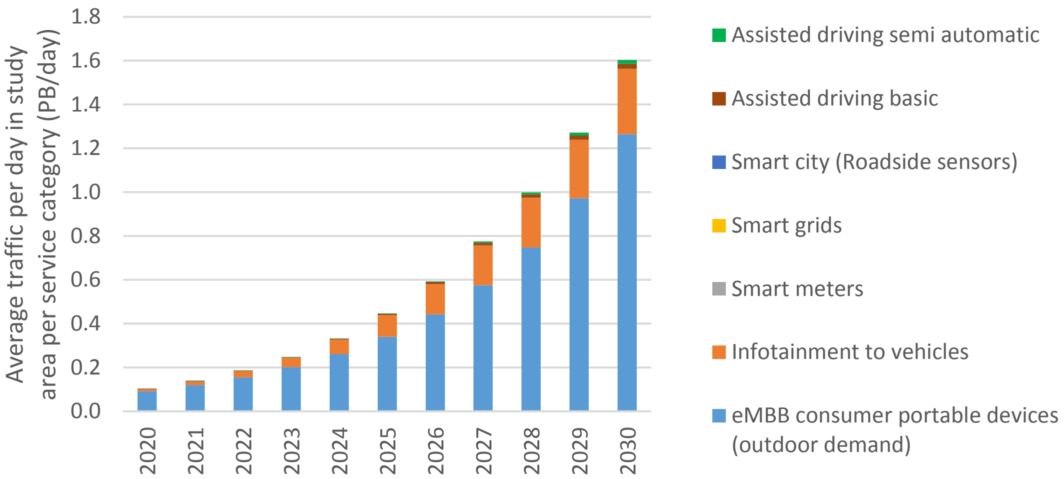



**Figure 2-6: Medium growth traffic forecast for the 5G multi-service scenario**

### 2.3.3 Low, medium and high demand profiles

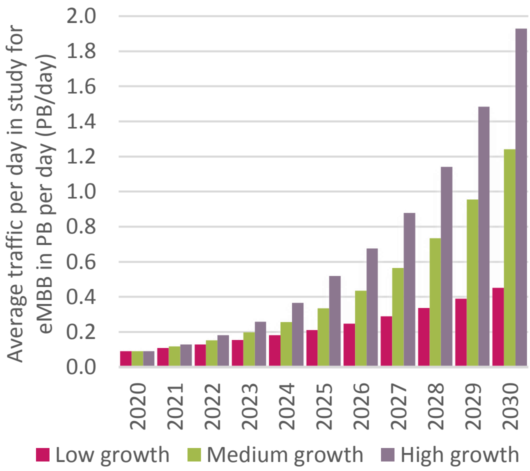
Finally, we determine the low and high traffic growth scenarios to apply to our business case analysis as discussed in Section 2.1. We only consider low and high forecasts for eMBB traffic volumes to consumer portable devices given that:

- This traffic volume dominates the overall multi-service traffic volume
- MTC traffic is more deterministic and less application dependent than eMBB services.

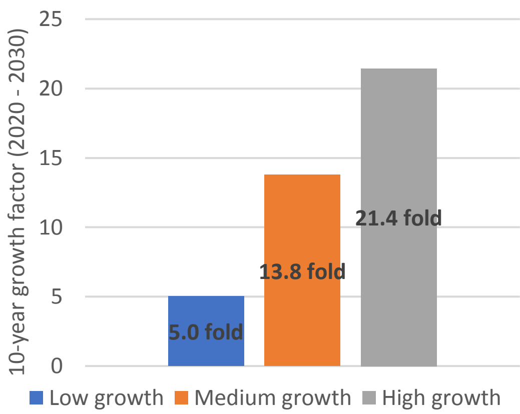
Having reviewed historic traffic volumes for the UK and a range of traffic forecasts for future years we assume:

- A low growth case with traffic volume growing with 21% CAGR in 2020 and declining to 16% CAGR by 2030
- A medium growth baseline case with a flat growth of 30% CAGR from 2020 to 2030
- A high growth case with a growth of 42% CAGR from 2020 to 2025 and stepping down to 30% CAGR from 2026 to 2030.

This results in the range of traffic volumes and 10-year growth factors given in Figure 2-7. In practice MNOs have some control over the traffic growth scenario that occurs which will be linked to the data plans offered and in turn the competition in the market and commercial tariffs evolution.




(a) Low, medium and high growth eMBB forecasts for the study area




(b) 10-year growth factors for low, medium and high growth eMBB cases

**Figure 2-7: Range of traffic volumes and 10-year growth factors**

## 2.4 Network dimensioning assumptions

### 2.4.1 High level overview of the cost model

WP2 has developed a network cost model that identifies the minimum cost deployment that can accommodate the traffic demand each year as defined in each evaluation case. A high-level overview of the network cost model is shown in Figure 2-8.

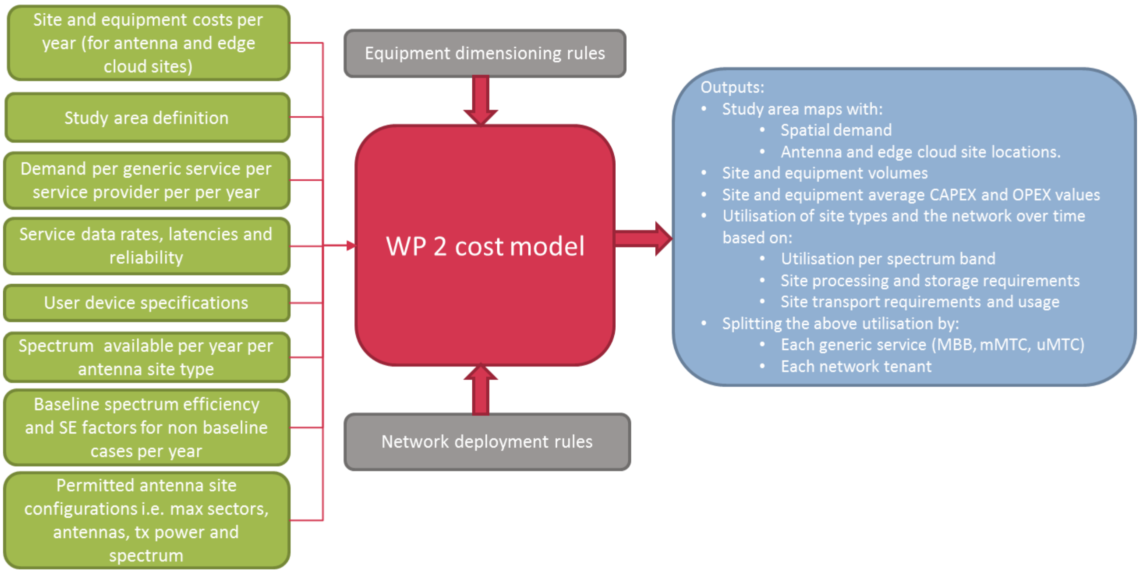



**Figure 2-8: Overview of WP2 cost model**

In each modelled year the cost model tool forecasts and distributes the demand into the demand sources (spatial-), and into hours of the day (temporal-distribution). The coverage and capacity module of the tool then serves the generated demand based on the current network deployment. Any leftover demand needs to be served by implementing network improvements (new/upgrade antenna sites) and improvement options are ranked by a merit function (of cost over benefit). Present value TCO is used for the merit-cost in the cost model tool. However, non-discounted network costs per year are presented in Section 3 with the present value calculation applied in the commercial assessment in Section 4.

A cost optimisation tool polls improvement options and decides on the set of network improvements that minimise cost while serving the offered demand. In each year, the costs reported correspond to the minimum-cost poll from the tool given a limited simulation time and, in reality, will be subject to availability of the polled site locations – we assumed that antenna sites can be placed on or at the furthest 25m from existing buildings. Use of such a building database prevented macrocell site placement in unsuitable locations, for example on the river or in parks.

Because network improvements are selected based on minimum cost over benefit, the tool implements different network improvements at different locations. The choice of improvement can depend on the extent of the area that lacks coverage, for example by choosing between a new macrocell or small cell. The amount of leftover demand will most likely define the bandwidth and number of antennas required on the antenna site and the amount of additional servers needed at the edge cloud, if any. Proximity to upgradeable antenna sites may mean that the tool selects an upgrade over a new site.

Detailed explanation on the modelling assumptions used are given in Appendix C which includes:

- Spectrum availability over time
- Spectrum efficiency evolution assumed over time

- Mapping of services to network layers based on service requirements (for example, high velocity traffic must be carried by macrocells).
- Site, equipment and transport costs

The study area is modelled between 2020 to 2030. A pixel granularity of 25m is assumed to achieve the best trade-off between the smallest expected cell sizes and sensible model run time.

Offered traffic is distributed in the model to match areas where we anticipate eMBB, MTC and V2I traffic will occur. Within this demand distribution we consider sources of demand including residential and business premises and thoroughfare points. In the case of thoroughfare points we assume that demand is generated along Motorways, major roads (known as A roads in the UK), less major roads (known as B roads), Minor roads and Railways. However, we do not include tunnelled railway in demand points as mobile coverage is likely to be provided by specialised solutions not considered as part of the wider outdoor network.

### 2.4.2 Starting network assumptions

The existing number of macrocell antenna sites in the area is based on:

- Finding the number, type and location of reported sites for a typical existing mobile operator in the area based on Ofcom's Sitefinder database [Ofc12].
- Placing new sites to target any unserved demand (in terms of both coverage and capacity) left by the starting set of sites based on the demand present by 2019 to obtain the 2020 starting network.

The selected example site portfolio used in Evaluation Case 1 is assumed to have a typical market share of 18%. With a starting set of 72 macrocell antenna sites from Sitefinder [Ofc12], this example network, targeting outdoor eMBB services to consumer portable devices, grows to approximately 130 macrocell antenna sites by 2020 via the cost model tool's network dimensioning for the medium traffic growth scenario. In a study area of 37.56 km$^2$, this 2020 site volume gives an average area of 0.289 km$^2$ per site or an Inter Site Distance (ISD) of 578 m (assuming hexagonal layout). This is largely in line with the ISD for urban macrocells from the ITU guidelines for evaluation of IMT-Advanced technologies [M.2135-1] of 570 m and the 500m ISD assumed in the medium case in Deliverable D3.2 [5GN-D32].

From 2020 to 2030, the model places new sites or upgrades existing sites to meet the growing demand of the services being modelled based on satisfying:

- Coverage requirements for each pixel of demand across the study area for each given service modelled.
- Busy hour capacity requirements given the combined spatial and temporal traffic volumes of the services modelled.

New sites will only be placed if spectrum and antenna upgrades are not more cost effective, in line with network planning rules entered in the model. Note that the ISD between macrocells cannot be less than 250m according to the network design rules outlined in Appendix C.

We assume that edge cloud sites can be located at the existing incumbent fixed telecoms exchange sites in the area. Based on economies of scale a C-RAN architecture is beneficial when there is a considerable aggregation at the edge cloud site (see Section 2.4.6), and to achieve such a level we calculated that the study area should include 6 edge cloud sites, chosen from the 32 existing exchange locations. Each edge cloud site was then serving on average 22 macrocells in 2020, and an increasing number of antenna sites thereafter. We calculated the maximum Euclidean distance between antenna and edge cloud site at 3.5km. Taking the route of the fibre into consideration, based on the G.826 routing factor of 1.5 [G.826], the maximum fibre length would not exceed 5.3km. The one-way latency in 5.3km of fibre is 26µs. Therefore, even CPRI, with latency requirements of 250µs could be supported by fibre in this dense urban scenario if 6 (out of 32) existing exchanges are used as the edge cloud sites.

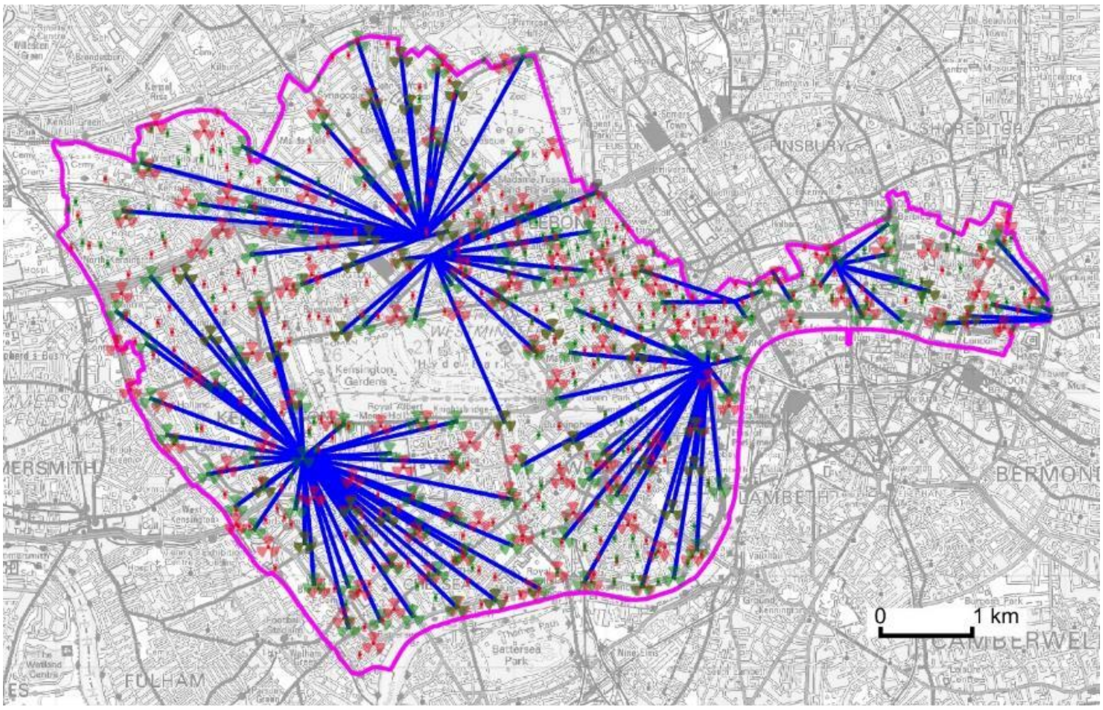



**Figure 2-9: Assumed edge cloud sites in the study area with antenna sites covered by each (blue) within the study area (magenta line).**

### 2.4.3 Network evolution assumptions

Permissible site configurations (power, number of sectors, antenna multiple input multiple output (MIMO) order and height) that the cost model can use are shown in Table 2-5. As time progresses, it is assumed that additional spectrum (both bandwidth and the number of bands), and MIMO that can be used at macro or small cell (SC) sites evolves as shown in Table 2-6.

Please note the following definitions of the frequency band names used in these tables:

- Sub-1GHz – 700, 800 and 900 MHz FDD bands
- Low band paired – 1800, 2100 and 2600 MHz FDD bands
- Low band unpaired – 2600 MHz TDD band
- Medium (unpaired band) – 3400-3600 MHz TDD band

**Table 2-5: Antenna site configurations supported in line with D3.2**

| Power amplifier class | Sectors | Transmit power | Antenna elements supported at site | Height |
|---|---|---|---|---|
| **Macrocells (At sub-1GHz and low paired spectrum and medium unpaired spectrum)** | 3 | 4W per MHz at sub-1GHz bands<br>2 W per MHz at low and medium bands | Macrocells @sub-1GHz and low bands: transitions from 2 to 4 antenna elements<br>Macrocells @ medium bands: transition from 32 to 64 antenna elements | 25 m |
| **Small Cells (At low and medium unpaired spectrum)** | 2 | Total EIRP of 40dBm | Transitions from 2 to 4 antenna elements | 8 m |

**Table 2-6: Antenna site configurations evolution over the 2020 to 2030 study period**

| Year | Macrocell configuration (per band) | Year | SC configuration (per band) |
|---|---|---|---|
| **2020** | Sub-1GHz: 2x15 MHz, 3 sectors, 2x2 MIMO<br>Low: 2x60 MHz, 3 sectors, 2x2 MIMO | **2020** | Low: 1x20 MHz, 2 sectors, 2x2 MIMO |
| **2021** | Sub-1GHz: 2x15 MHz, 3sectors,2x2 MIMO<br>Low: 2x60 MHz, 3 sectors, 2x2 MIMO<br>**Med: 1x20 MHz, 3 sectors, 32 Massive MIMO (MMIMO)** | **2023** | Low: 1x20 MHz, 2 sectors, 2x2 MIMO<br>**Med: 1x20 MHz, 2 sectors, 2x2 MIMO** |
| **2023** | Sub-1GHz: **2x25 MHz**, 3sectors,**4x2** MIMO<br>Low: 2x60 MHz, 3 sectors, **4x2** MIMO<br>Med: 1x20 MHz, 3 sectors, 32 MMIMO | **2024** | Low: 1x20 MHz, 2 sectors, **4x2** MIMO<br>Med: **1x40 MHz**, 2 sectors, 4x2 MIMO |
| **2027** | Sub-1G: 2x25 MHz, 3sectors, 4x2 MIMO<br>Low: 2x60 MHz, 3 sectors, 4x2 MIMO<br>Med: 1x20 MHz, 3 sectors, **64** MMIMO | | |

### 2.4.4 Example CAPEX and OPEX for different antenna site specifications

Detailed cost assumptions are given in Appendix C. By way of illustrating cost assumptions, six different macrocell site specifications have been selected, as shown in Table 2-7. We first calculate indicative CAPEX and then OPEX values.

**Table 2-7: Six different macrocell configurations and their key features**

| Specification index | Differentiating features | # Sectors / site | Number of antenna elements, Bandwidth (MHz) in each band | | | |
|---|---|---|---|---|---|---|
| | | | **Sub-1GHz** | **Low** | **Medium** | **High** |
| **1** | | 3 | 0, 0 | 2, 20 | 0, 0 | 0, 0 |
| **2** | Double bandwidth | 3 | 0, 0 | 2, 40 | 0, 0 | 0, 0 |
| **3** | Additional bands | 3 | 2, 15 | 2, 60 | 0, 0 | 0, 0 |
| **4** | Additional band, MMIMO | 3 | 2, 15 | 2, 60 | 32, 20 | 0, 0 |
| **5** | 4x2 MIMO | 3 | 4, 25 | 4, 60 | 32, 20 | 0, 0 |
| **6** | MMIMO | 3 | 4, 25 | 4, 60 | 64, 20 | 0, 0 |

Using the site costs detailed in Appendix C, Table 2-8 summarises CAPEX elements that incur for D-RAN and C-RAN configurations. Some CAPEX elements are indifferent to antenna site configuration, for example site civil works and acquisition are the same regardless of the site being with bare metal BBU or its processing is performed at the edge cloud.

**Table 2-8: CAPEX elements which are affected by D-RAN and C-RAN configurations**

<table>
<tr><th></th><th>D-RAN</th><th>C-RAN</th><th>Notes</th></tr>
<tr><td>Civil works & acquisition</td><td colspan="2">Indifferent to configuration</td><td rowspan="6">Practically indifferent to configuratio n</td></tr>
<tr><td>Labour</td><td>More expensive by £0.2k per macrocell antenna site because more upgrades are performed</td><td>More economical</td></tr>
<tr><td>Antenna site transport</td><td>May benefit from initial deployment with more economical managed fibre for sub 10Gbit/s products. However, growing demand may increase bandwidth needed beyond 10 Gbit/s at which point dark fibre products are lower cost on a 10-year TCO basis (higher CAPEX than managed fibre but lower OPEX) so that eventually macrocell antenna sites in hotspot areas will be upgraded to dark fibre.</td><td>Dark fibre solutions needed with high CAPEX but low on-going OPEX (which gives a better 10-year TCO than managed fibre for bandwidths greater than 10Gbit/s)</td></tr>
<tr><td>Edge cloud transport</td><td>N/A</td><td>Trivial</td></tr>
<tr><td>Antennas/feeder</td><td colspan="2">Indifferent to configuration</td></tr>
<tr><td>RF front end</td><td colspan="2">Indifferent to configuration</td></tr>
<tr><td>Processing</td><td>Based on cost for bare metal BBU</td><td>Based on cost for servers</td><td>Analysed further</td></tr>
</table>

To isolate the CAPEX dynamics between D-RAN and C-RAN, Table 2-9 calculates the number of bare metal reference BBU and of servers & cabinets at the edge cloud. As reference BBU we refer to the base band required for 3 sectors, 2x2 MIMO and 20 MHz of bandwidth, see Table 5.3 in [5GN-D22]. The number of processing servers at the edge cloud depends on the spectrum utilisation and level of aggregation. As an example, we dimension processing servers assuming 5%, 25%, 50% PRB utilisation at sub-1GHz, low and medium bands, respectively, and for 29 antenna sites per edge cloud. This assumes that the sub-1GHz is utilised primarily for serving indoor locations, which are out of scope in this project, and occasionally hard to reach outdoor locations which in the sake of this example amounts to 5% utilisation of the sub-1GHz band. The other two loading levels correspond to a 6 and 3 dB reduction from the maximum licence power, for low and medium bands respectively, which are typical levels for real deployments. Deviations of network loading and aggregation level are discussed further in Section 2.4.5 and Section 2.4.6.

**Table 2-9: Indicative calculation of number of bare metal reference BBU (3 sectors, 2x2 MIMO, 20 MHz) and of servers at the edge cloud for D-RAN and C-RAN configurations**

| Specification index | Number of bare metal reference BBU | Number of servers | Number of cabinets |
|---|---|---|---|
| **1** | 1 | 0.24 | 0.034 |
| **2** | 2 | 0.48 | 0.034 |
| **3** | 4 | 0.79 | 0.069 |
| **4** | 8 | 2.17 | 0.138 |
| **5** | 13 | 3.10 | 0.207 |
| **6** | 15 | 3.79 | 0.241 |

Table 2-10 calculates the indicative CAPEX for macrocell antenna site installation using 2017 prices, ignoring end-of-life cycles and cost variations with time – CAPEX typically erodes with time.

**Table 2-10: Indicative calculation of CAPEX for macrocell antenna site installation, ignoring end-of-life cycles and cost variations with time, for D-RAN and C-RAN configurations, in £k**

| Specification index | D-RAN | C-RAN | | |
|---|---|---|---|---|
| | | Total | Server | Cabinet |
| **1** | 2.5 | 2.31 | 1.57 | 0.74 |
| **2** | 5.0 | 3.88 | 3.14 | 0.74 |
| **3** | 10.0 | 6.63 | 5.16 | 1.48 |
| **4** | 20.0 | 17.07 | 14.12 | 2.95 |
| **5** | 32.5 | 24.60 | 20.17 | 4.43 |
| **6** | 37.5 | 29.82 | 24.66 | 5.17 |

To consider end-of-life cycles, Table 2-11 calculates indicative CAPEX per macrocell antenna site over 10 years, again using 2017 prices and ignoring cost variations with time. Here COTS processing equipment at edge cloud sites are assumed to have a shorter lifetime than those of telco grade basestations on D-RAN antenna sites. Note, while a shorter life time is applied for processing via servers at edge cloud sites in the model than for telco grade BBUs at antenna sites, we do not improve the rate of processing achieved at the edge cloud sites due to this faster refresh cycle. This may make our C-RAN processing costs more pessimistic than could be achieved in practice.

**Table 2-11: Indicative calculation of CAPEX over 10 years for macrocell antenna site installation, considering end-of-life cycles and ignoring cost variations with time, for D-RAN and C-RAN configurations, in £k**

| Specification index | D-RAN | C-RAN |
|---|---|---|
| **1** | 2.5 | 4.7 |
| **2** | 5.0 | 8.6 |
| **3** | 10.0 | 14.4 |
| **4** | 20.0 | 38.3 |
| **5** | 32.5 | 54.9 |
| **6** | 37.5 | 66.8 |

To consider price erosion, Table 2-12 concludes with the indicative CAPEX per macrocell antenna site over 10 years. As discussed in Appendix C, we assume that CAPEX assumed for processing at the edge cloud site does not erode over time as a review of costs of high end processors over time has shown that these tend to be stable over time. Additionally, our CAPEX values for edge cloud processing equipment include a mix of equipment costs (which may erode over time) and labour costs to assemble the correct configuration of COTS modules required (which will grow over time).

**Table 2-12: Indicative calculation of CAPEX over 10 years for macrocell antenna site installation, considering end-of-life cycles and cost variations with time, for D-RAN and C-RAN configurations, in £k in 2025**

| Specification index | D-RAN | C-RAN |
|---|---|---|
| **1** | 1.9 | 4.7 |
| **2** | 3.8 | 8.6 |
| **3** | 7.6 | 14.4 |
| **4** | 15.2 | 38.3 |
| **5** | 24.7 | 54.9 |
| **6** | 28.5 | 66.8 |

This concludes the CAPEX calculations. Note that C-RAN costs less in terms of CAPEX per macrocell site installation if the life cycle of equipment is ignored. If end-of-life cycle is taken into account, then C-RAN becomes more expensive, but this is dependent on the utilisation of resources – we assumed 5%, 25%, 50% PRB utilisation at sub-1GHz, low and medium bands as explained above, respectively. When demand increases, the resource utilisation of the antenna sites is likely to increase, which increases the number of servers but not that of BBUs, thus CAPEX with virtulisation may become costlier.

Table 2-13 summarises OPEX elements that are incurred for D-RAN and C-RAN configurations. Some OPEX elements are indifferent to antenna site configuration, for example site rental and Business rates & power are the same regardless of the site being with bare metal BBU or its processing is performed at the edge cloud.

**Table 2-13: OPEX elements which are affected by D-RAN and C-RAN configurations**

| | D-RAN | C-RAN |
|---|---|---|
| **Macrocell antenna site rental** | Indifferent to configuration | Indifferent to configuration |
| **Macrocell antenna site business rates and power** | Indifferent to configuration | Indifferent to configuration |
| **Macrocell antenna site maintenance visits** | More expensive by £3.1k per macrocell antenna site per year | More economical |
| **Macrocell antenna site RAN equipment licensing** | More expensive by £0.8k per macrocell antenna site per year | More economical |
| **Macrocell antenna site transport** | More expensive by £1.1k per macrocell antenna site per year | More economical |
| **Edge cloud cabinet rent & utilities** | N/A | Based on number of cabinets, see Table 2-14 |
| **Edge cloud operating overhead** | N/A | More expensive by £0.291k per macrocell antenna site per year |
| **Edge cloud RAN equipment licensing** | N/A | Based on number of cabinets, see Table 2-14 |
| **Edge cloud transport** | N/A | Trivial |

Table 2-14 calculates the indicative macrocell antenna site annual OPEX. The number of processing servers at the edge cloud depends on the spectrum utilisation and level of aggregation. Processing servers are dimensioned assuming 5%, 25%, 50% PRB utilisation at sub-1GHz, low and medium bands, respectively, and for 29 antenna sites per edge cloud, similar to the CAPEX indicative calculations above.

**Table 2-14: Indicative calculation of annual OPEX that is dependent on the number of cabinets, in £k in 2025**

| Specification index | Cabinet rent and utilities | Edge cloud RAN equipment licencing |
|---|---|---|
| 1 | 0.30 | 0.25 |
| 2 | 0.30 | 0.50 |
| 3 | 0.59 | 0.99 |
| 4 | 1.19 | 1.98 |
| 5 | 1.78 | 3.22 |

Figure 2-10 shows the breakdown of CAPEX (10-year value with price erosion) and OPEX for a D-RAN or C-RAN macrocell antenna site for each specification.

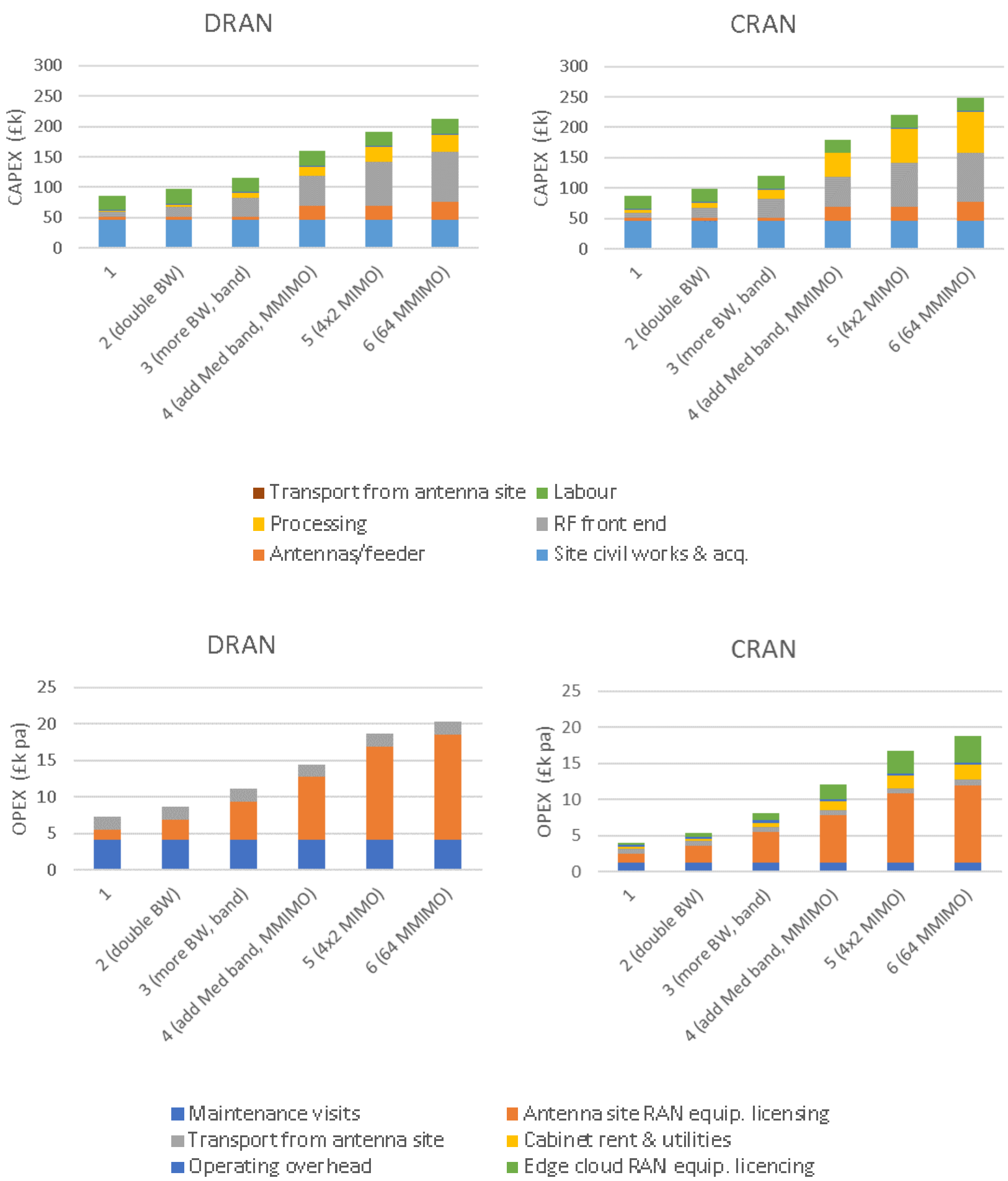



**Figure 2-10: Macrocell related antenna and edge cloud site CAPEX and OPEX for different antenna site specifications, assuming 5%, 25%, 50% PRB utilisation at sub-1GHz, low and medium bands, respectively, and 29 macrocell antenna sites per edge cloud site**

### 2.4.5 Effect of network load on D-RAN C-RAN cost comparison

In Section 2.4.4 the CAPEX and OPEX of a new macrocell antenna site have been calculated based on 5%, 25%, 50% PRB utilisation at sub-1GHz, low and medium bands, respectively. This section discusses how the level of network loading affects costs.

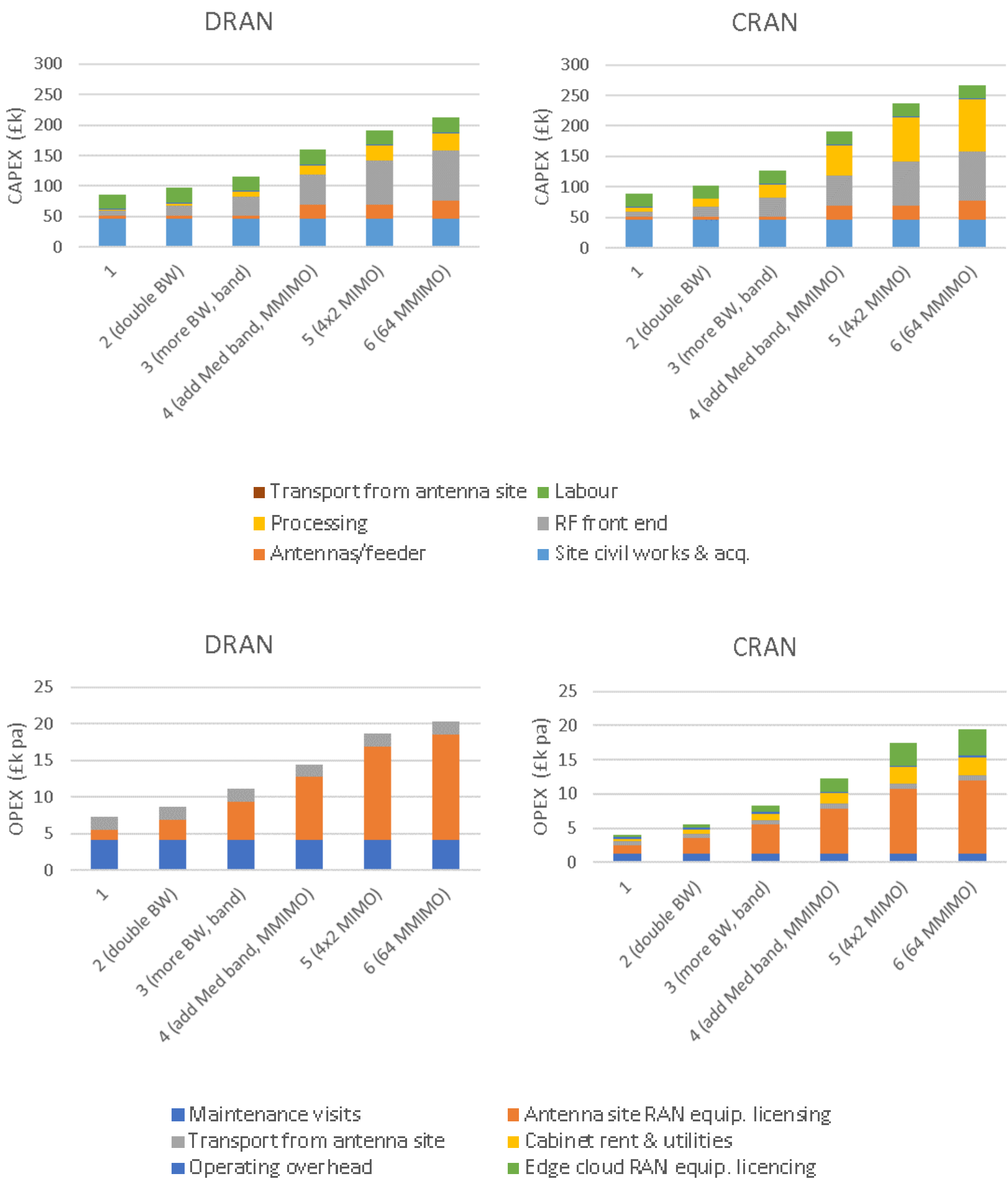


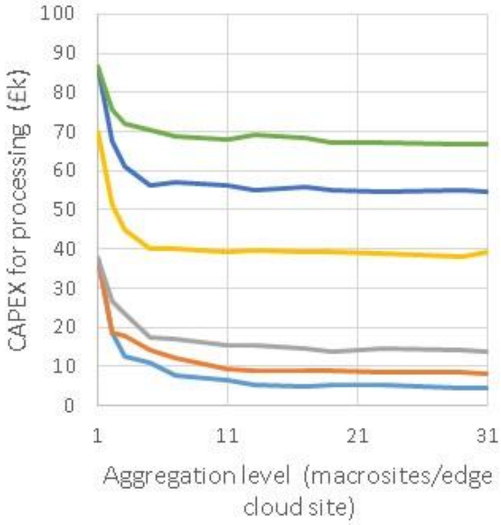

**Figure 2-11: Macrocell antenna site CAPEX and OPEX for different site specifications, assuming 20%, 45%, 60% PRB utilisation at sub-1GHz, low and medium bands, respectively, and 29 macrocell antenna sites per edge cloud site**

The level of network loading affects the number of servers needed initially, and consequently the number that needs refreshment due to end-of-life cycles, because the number of cores at the edge cloud is dimensioned to the level of network utilisation, rather than its maximum capacity. As a sensitivity analysis we increased the level of utilisation to 20%, 45%, 60% PRB utilisation at sub-1GHz, low and medium bands, respectively. Figure 2-11 shows the breakdown of CAPEX and OPEX for a D-RAN or C-RAN macrocell antenna site for each specification. Increase in network loading seems to lead to increase in CAPEX and OPEX of macrocell antenna sites, however the increase appears to be moderate.

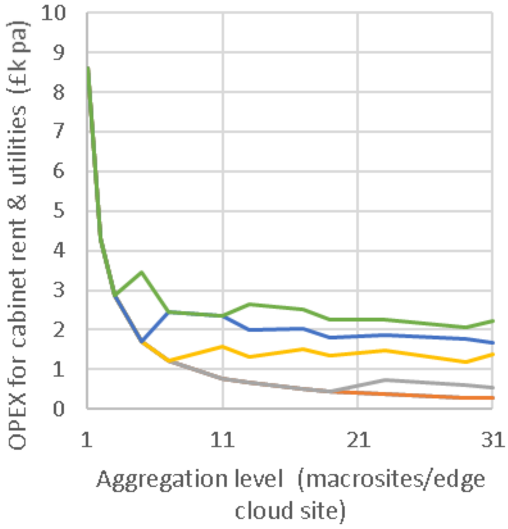
### 2.4.6 Edge cloud site costs and economies of scale

In Section 2.4.4 the CAPEX and OPEX of a new macrocell antenna site have been calculated based on 29 macrocell antenna sites per edge cloud site. This section discusses how the level of aggregation affects costs.

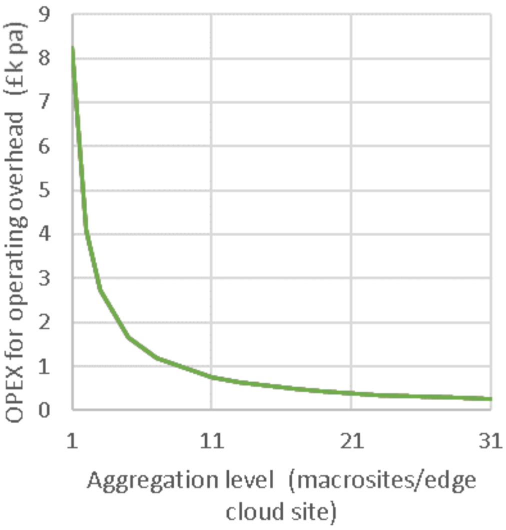
The level of aggregation affects the number of servers and cabinets, since these need to be in integer numbers. Figure 2-12 shows how cost elements are affected by different levels of aggregation. Benefits from economies of scale seem to flatten before 10 macrocell antenna sites per edge cloud site. These figures demonstrate that a relatively modest number of sites need to be aggregated in order to achieve cost-per-core close to the asymptote. Additional OPEX savings can be achieved with higher levels of aggregation, but these are small compared to the CAPEX assumptions. Benefits become marginal with more than 30 macrocell antenna sites aggregated at an edge cloud site, though this could be higher for lower capacity macrocell antenna sites.



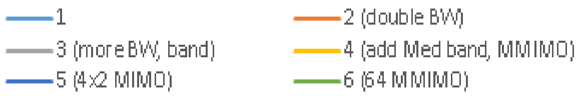

(a) CAPEX for processing servers and cabinets




(b) OPEX for cabinet rent & utilities




(c) OPEX for operating overhead




(d) Legend

**Figure 2-12: CAPEX and OPEX elements that are affected by level of aggregation**

### 2.4.7 Accommodating more challenging non-eMBB service requirements

In Section 2.4.2 we explained how the network grew from the 72 initial macrocell antenna sites in 2017 to approximately 130 by 2020. This increase was performed to meet both coverage and capacity requirements for outdoor eMBB services to consumer portable devices. In terms of coverage this was assessed by means of a link budget to provide outdoors 10 Mbps DL and UL with 95% cell-area coverage-confidence. From the link budget, we estimated the range that corresponds to the above QoS criteria at the candidate frequency bands and created new macro- and small-cell sites to ensure that all demand points fell within the range of their best server.

For non eMBB services a similar methodology was followed as in eMBB services. A link budget relatable to non eMBB services was drafted, and key features of such services, for example indoor penetration depth and confidence requirement, were flexed to observe their effect on macrocell ranges. Table 2-15 summarises the differences between eMBB and non-eMBB services in terms of link budget methodology.

Single-service (eMBB) network-cost assessment was based on network dimensioning that corresponds to an eMBB link budget. In the case of multi-service (for example eMBB plus smart meter) the network dimensioning can be done with any of these techniques:

- Dimension for the blended eMBB and smart meter traffic, where outdoor locations need coverage according to eMBB link budget parameters and indoors according to the smart meter link budget – This reveals how much Total Cost of Ownership (TCO) increases as a result of the obligation to serve smart meter traffic. In this dimensioning technique, the smart meter service is constantly 100% within 2020-30 in the multi-service runs, and the TCO varies.
- Dimension for eMBB neglecting unserved smart meter traffic – This would reveal how much served smart meter traffic results as collateral from the TCO of eMBB-focused network evolution. Reversely it would show how much unserved smart meter traffic results from access to a single InP and thus potential for increase in coverage by tapping on a second InP. In this technique TCO is constant between the single- and multi-service runs, and the service percentage of smart meter varies.

For the modelling in 5G NORMA the technique described in the first bullet point was applied.

**Table 2-15: Differences between eMBB and non-eMBB services in terms of link budget methodology**

| Link budget element | eMBB | Non-eMBB |
|---|---|---|
| **Indoor penetration** | We dimensioned the network to provide service outdoors at an application rate 10 Mbps DL and UL. We did not specifically dimension for indoor eMBB because incidentally sufficient low-throughput coverage is achieved indoors when high-throughput coverage is achieved outdoors. | For smart meter connectivity we dimensioned for deep indoors, whereas for vehicle connectivity we assumed that the antennas were placed on the chassis and thus outdoors |
| **Antenna elements at the mobile or fixed UE** | We dimensioned the network assuming 2 antenna elements at handheld devices | Smart meters modelled as equipped with 1 antenna element. Vehicles equipped with 8 and benefiting from directivity gains. |
| **Reliability** | The link budget is time-static and therefore does not have a margin that is related to increased reliability requirement, which is related to transmission success rates of data packets. Reliability was considered indirectly by setting cell-area coverage-confidence at 95%. | To factor in the increased reliability requirement of uMTC and mMTC, compared to eMBB, in the former two we considered increasing the coverage confidence of location variability to 99-99.999% |
| **Multi-connectivity and best serving site fall back** | We dimensioned the network assuming the UE camps on its best serving site, which could be a macro- or small-cell, according to handover criteria with preference to higher frequency bands unless the UE travelled with high velocity | We dimensioned the network assuming the UE can benefit from multi macrocell connectivity at sub-1GHz band. We estimated the distribution of SINR from each serving cell in the UE's vicinity, and then employed multivariate normal distribution statistics to assess the probability of communication failure. |
| **Narrowband transmission, half baud rate, repetition, relay/buddy mode** | Not applicable or not considered in network dimensioning | We reserved these techniques for provision of connectivity for UE locations that are more challenging than the service range that results without these techniques. For example, a smart meter at far distance from any macrocell and at a basement/cellar would be unserved without a narrowband transmission, but with such it would be served. As we considered such occurrences limited we did not calculate their effect on increased network resources. |

Table 2-16 calculates the expected ranges and inter-site distances that correspond to two examplary non-eMBB services. Note that, even though the coverage confidence is high the example ISD exceed these from what has been envisioned for 2020 in central London, 500 m.

**Table 2-16: Expected ranges and inter-site distances that correspond to two example non-eMBB services, assuming 800 MHz spot frequency, 25 m BS antenna height, 1.5 m MS antenna height, urban Hata pathloss model**

| Link budget element | Outdoor eMBB 10 Mbit/s | Indoor smart meter | On vehicle I2V |
|---|---|---|---|
| Number of MS antenna elements | 2 | 1 | 4 |
| Receiver diversity gain, dB | 3 | 0 | 6 |
| Shadowing standard deviation, dB | 6.9 | 6.9 | 6.9 |
| Penetration loss mean, dB | 0 | 15 | 0 |
| Penetration loss standard deviation, dB | 0 | 8 | 0 |
| Cell-area coverage-confidence | 95% | 99.9% | 99.9% |
| Cell-edge coverage-confidence | 87% | 97% | 97% |
| Fade margin, dB | 7.8 | 32.1 | 17.6 |
| MAPL, dB | | 122.6 | 147.5 |
| UE height, m | | 1.5 | 1.4 |
| Range, m | | 759 | 3802 |
| ISD, m | | 1315 | 6585 |

# 3 Cost analysis of 5G NORMA

This section describes the results of the cost analysis performed for the three evaluation cases addressed in this report. In Evaluation Case 1 a cost assessment for a virtualised C-RAN network architecture is presented. The costs are compared with a D-RAN architecture, which is the network deployment approach typically applied by MNOs for current mobile radio generations. Evaluation Case 1 is employed also as baseline for the other evaluation cases presented in the report. Evaluation Case 2 corresponds to a multi-tenancy situation, where different tenants share the infrastructure. Evaluation Case 3 analyses the additional cost associated with dimensioning a C-RAN network for multiple slices, where one slice is eMBB and the other slices are fixed IoT and mobile connected vehicles.

In all three evaluation cases CAPEX, OPEX and TCO are calculated. Evaluation cases 1 and 2 are accompanied by sensitivity analysis results, where several parameters were selected to be varied from the baseline setting to observe their effect on the cost savings or penalties. In Evaluation Case 3, we introduced incrementally different slices, which can be considered as a sensitivity analysis to the penalties of dimensioning a 5G NORMA network for multiple services.

Note that all costs presented here are non-discounted RAN costs and do not include core networking costs, spectrum fees or administrative costs.

## 3.1 The C-RAN/D-RAN case

This section describes Evaluation Case 1 which is the cost comparison between C-RAN and D-RAN network architectures, with key assumptions regarding the study area definition, cost assumptions and network dimensioning already given in Section 2. The section finishes with the sensitivity analysis, where the following three parameters are flexed: traffic evolution, cost of transport network elements, and cost of edge cloud sites.

### 3.1.1 Baseline case

#### 3.1.1.1 TCO Results

In this section we show the major cost drivers and the TCO comparison between the C-RAN and D-RAN configurations. In both configurations, the 11-year TCO period has been partitioned into the cost drivers shown in Figure 3-1. The inner circles show the three network elements employed in the analysis: macrocell antenna sites, small cell antenna sites and edge cloud sites. The intermediate and external circles show the CAPEX and OPEX components. The annotated percentages and dimensions of the pie-slices of both graphs are relative to the C-RAN TCO, so that direct comparisons between the percentages on these two graphs are possible. Reduction in required network investment in the D-RAN network, compared to C-RAN, is marked on the graph as functionality gap.

For the macrocell and small cell antenna sites the OPEX values are higher than the CAPEX values. This is because OPEX is accumulated over the study period of 11 years, i.e. 2020-30, whereas CAPEX is incurred when network expansion is needed – in the form of new sites or site upgrades – or when equipment is refreshed at the end of a life cycle.

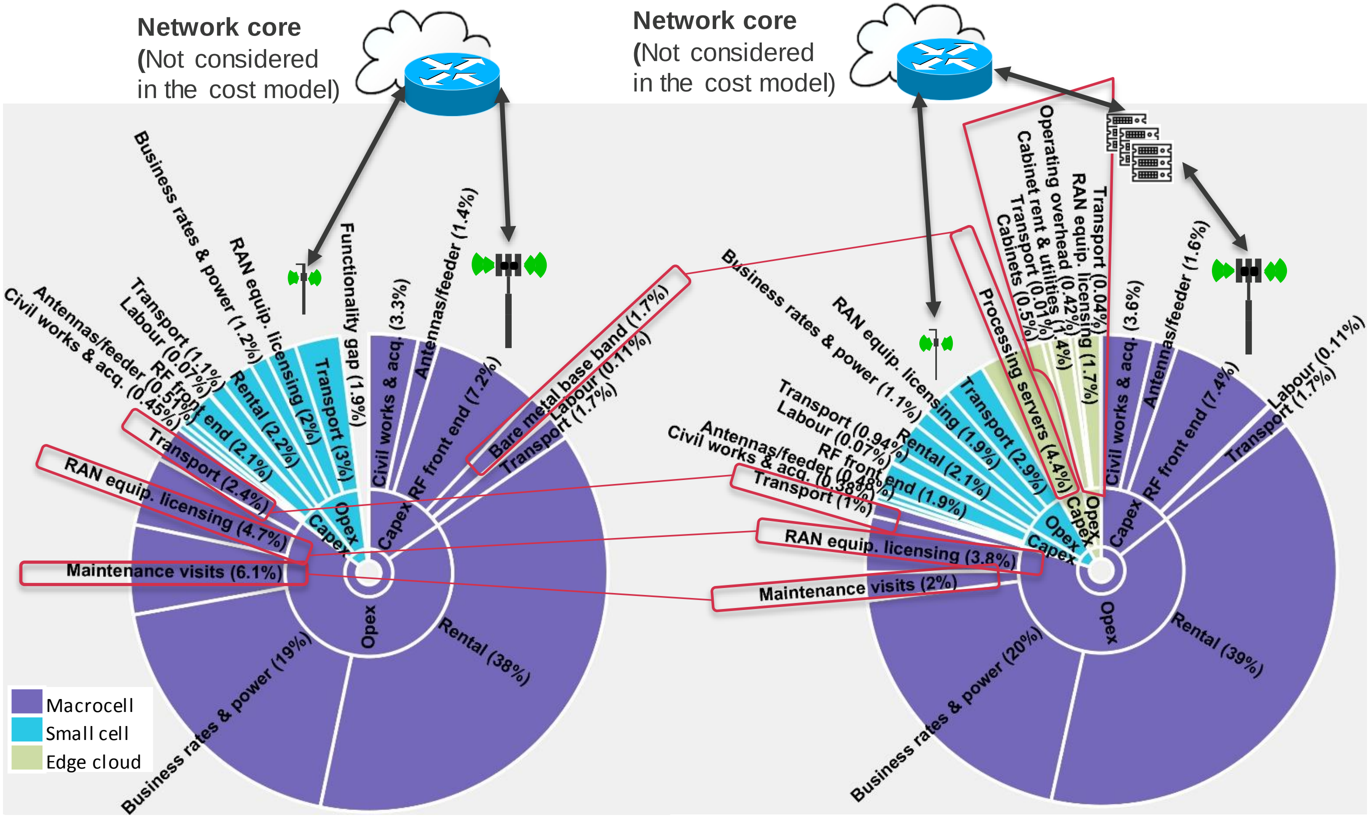



**Figure 3-1: Cost drivers in the D-RAN (left) and C-RAN (right) cases**

In C-RAN configuration the edge cloud sites correspond to the smallest part of the investment. CAPEX investment in processing servers at the edge cloud sites replaces the bare metal base band D-RAN CAPEX. Note that, although server CAPEX results in increased cost, the associated OPEX elements counterbalance CAPEX, but only to a certain degree. More specifically, the 11-year total D-RAN OPEX comprising macrocell transport, RAN equipment licensing and visits for maintenance become considerably reduced in the C-RAN case, but similar edge cloud OPEX (noting that additional costs from edge cloud sites are subject to the existing infrastructure set and migration path of the MNO as explored later in our sensitivity analysis). This trade-off, virtualisation leading to increased CAPEX but lower OPEX, means that at least in this baseline cost comparison there is no clear cost advantage of virtualisation.

Another observation from the cost comparison is that any cost advantage in reduction of macrocell antenna site CAPEX and OPEX through virtualisation can only accrue up to 15% of TCO. The sum of the circled cost elements of D-RAN in Figure 3-1 that can be reduced in the C-RAN case amount to 15%. This means that the cost trade-off between bare metal and edge cloud can only influence a relatively small percentage of TCO, and the biggest cost elements – antenna site rent, business rates[7] and power take more than 50% of TCO – are unchanged.

TCO for C-RAN and D-RAN are shown in Figure 3-2. TCO of the two configurations are similar, and in some years C-RAN is more expensive than D-RAN whereas in other years the opposite is observed. This is because the trade-off between increased CAPEX for virtualisation and lower OPEX is balanced. Table 3-1 shows the total values of CAPEX, OPEX and TCO for the sum of the period 2020-2030. D-RAN CAPEX is 17.7% lower than the C-RAN CAPEX. Note that CAPEX is around 25% of the total TCO. However, there is a cost saving in OPEX by about 2% and this leads to C-RAN being 2% more expensive than D-RAN in terms of TCO.

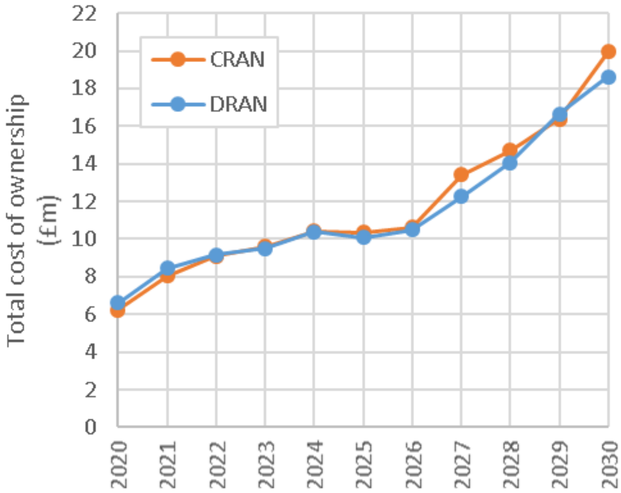



**Figure 3-2: TCO per year for the C-RAN and D-RAN configurations**

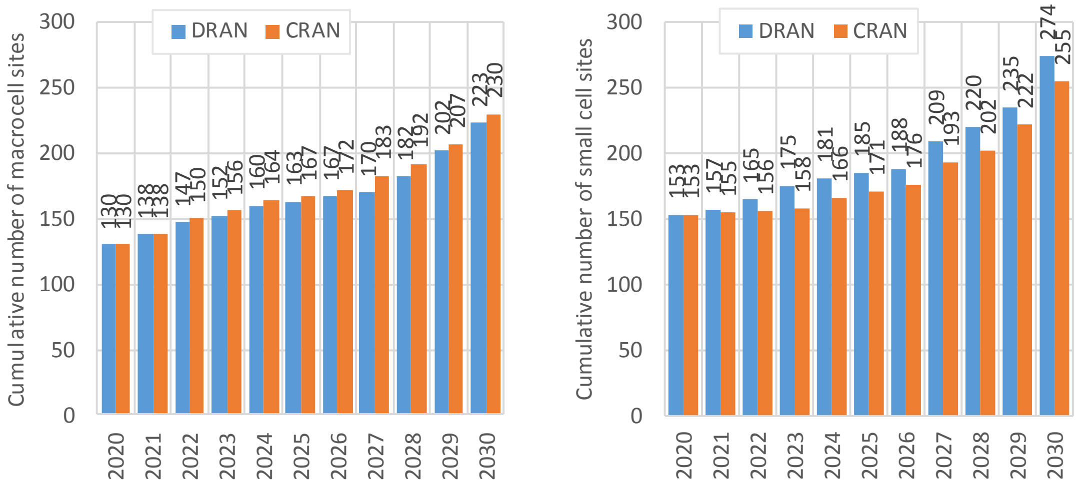
**Table 3-1: Comparison of C-RAN and D-RAN, sum over period 2020-2030**

| | D-RAN (£m) | C-RAN (£m) | C-RAN costs compared to D-RAN |
|---|---|---|---|
| CAPEX | 25 | 30 | +17.7% |
| OPEX | 101 | 99 | -2.0% |
| TCO | 126 | 129 | +2.0% |

[7] Business rates are taxes paid on non-residential properties and applicable in the UK.

The increase in the CAPEX investment over time is caused by the number of network elements deployed in the study period. Figure 3-3 shows the evolution of macrocell and small cell antenna sites to meet the demand in the study area over time. The baseline network evolves to meet the demand in the area over time. In the study period, the number of macrocell antenna sites increases from 130 to 230 and 130 to 223 in the C-RAN and D-RAN cases, respectively. However, the number of small cell antenna sites increases from 153 in 2020 to 255 and 274 in 2030 for C-RAN and D-RAN cases, respectively.

In Section 2.4 we compared the cost of an additional macrocell in D-RAN and C-RAN configurations for different specifications for frequency band and antennas supported. There, we showed that the macrocells with higher specifications become considerably more expensive from a 10-year TCO perspective with C-RAN configuration, when compared against D-RAN. This cost penalty for high-spec C-RAN macrocells is compounded when the spectrum utilisation is high, because processing at the edge cloud server is dimensioned for utilised resources with a margin whereas bespoke BBU hardware is dimensioned for maximum utilisation from the outset, see Figure 2-11. – Herein, we remind the reader that by macrocell with high-spec or specifications we mean a macrocell that is equipped with many antenna elements and increased band & bandwidth support. – A a consequence, the cost-optimiser installs less new macrocells but instead upgrades existing macrocells to higher specification macrocells when in D-RAN, and newer macrocell sites with lower specifications rather than upgrading existing ones to higher specifications when in C-RAN, see Figure 3-4.




(a) Cumulative number of macrocell antenna sites

(b) Cumulative number of small cell sites

**Figure 3-3: Number of macrocell and small cell antenna sites**

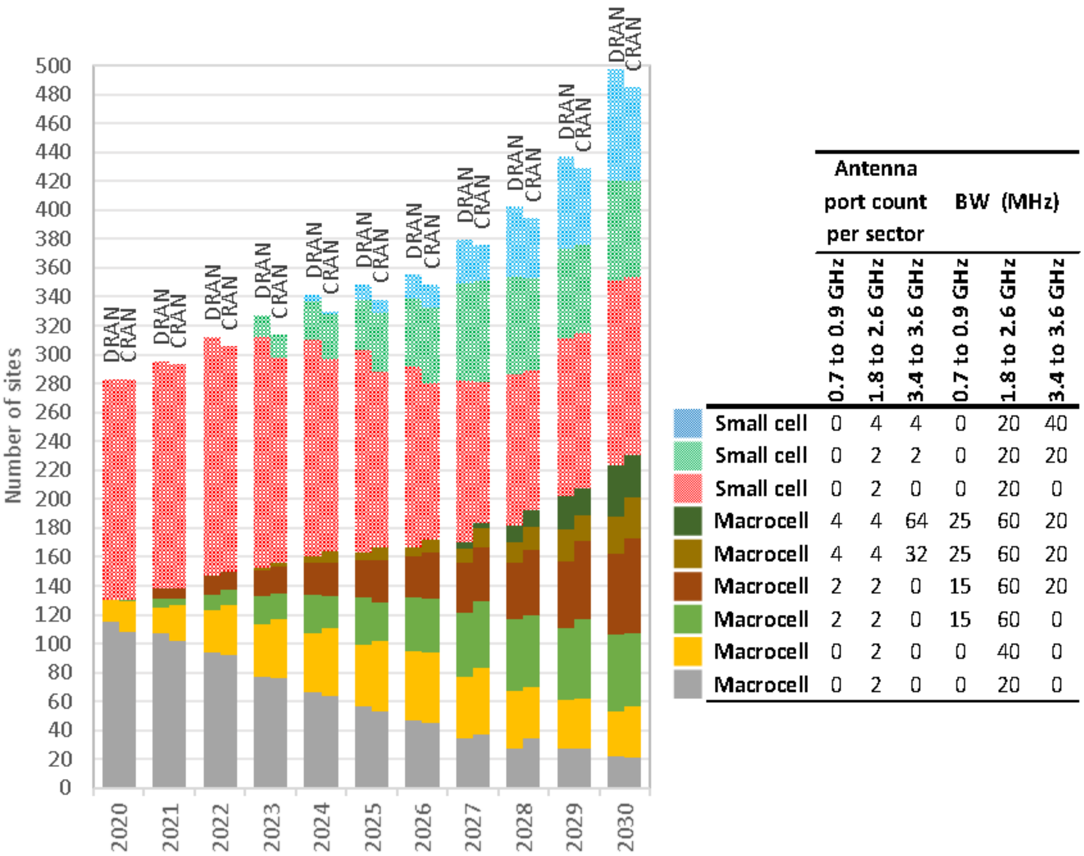



**Figure 3-4: Breakdown of the number of sites according to their specifications. The legend summarises for each modelled band the number of antennas ports per antenna site sector, and the channel BW.**

### 3.1.1.2 CAPEX results

The CAPEX results for the D-RAN and C-RAN configurations are provided in Figure 3-5. For all the years the CAPEX of C-RAN is higher than that of D-RAN. The macrocell CAPEX dominates in both the C-RAN and D-RAN configurations. The CAPEX of macrocell antenna sites is generally lower with C-RAN due to use of simpler RRH-based equipment compared to an additional full radio protocol stack processing implementation as in the D-RAN case.

The edge cloud site CAPEX – only present in the C-RAN case – grows more significant than in earlier years over time as the capacity to be processed at the edge cloud increases with time.

Note that small cells use D-RAN, so the small cell CAPEX contribution is similar between C-RAN and D-RAN configurations. However, there are slightly different volumes of small cells between these two scenarios as networks evolve differently due to the higher cost of D-RAN macrocell antenna sites compared with C-RAN macrocell antenna sites as discussed earlier.

Figure 3-6 shows the CAPEX breakdown for only the macrocell antenna sites for D-RAN and C-RAN cases. RF front end dominates CAPEX in both configurations and increases significantly over time as it scales with number of frequency bands, bandwidth and antennas installed at the antenna site which grow over time.

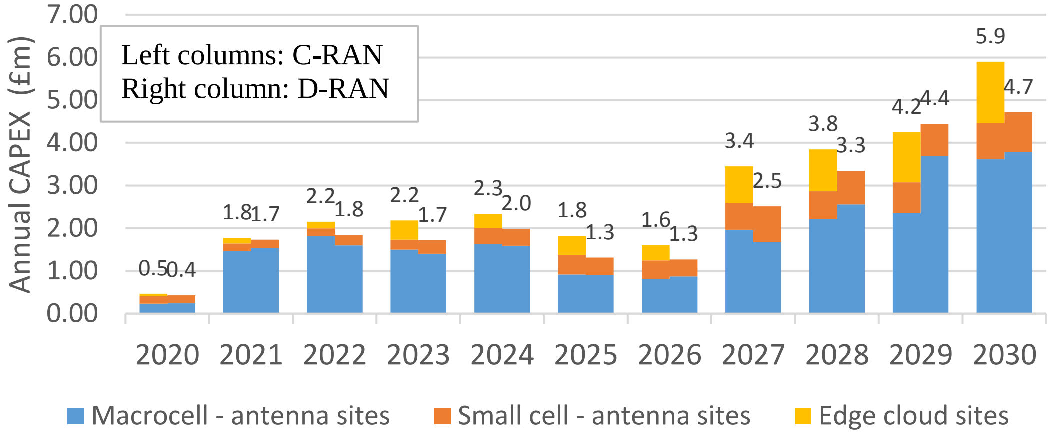



**Figure 3-5: CAPEX per year, broken down by sites**

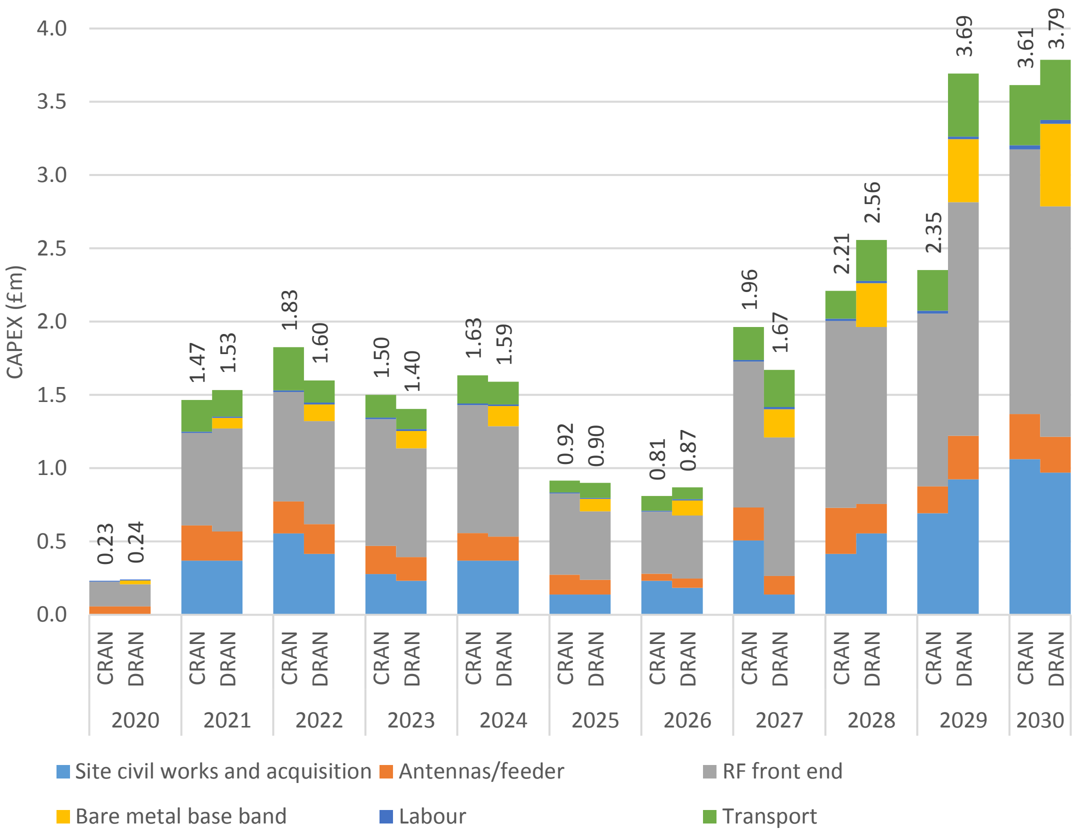



**Figure 3-6: CAPEX breakdown per year, macrocell antenna sites**

Figure 3-7 shows the C-RAN conversion CAPEX which is spent before 2020 to migrate the existing network from D-RAN. This additional CAPEX conversion-cost was calculated at £4.2m for the study area. This is 62% of the typical annual spend for a D-RAN network in the year of conversion. According to expectations, to support virtualised network functions macrocell antenna site transport needs to be upgraded from managed- to dark-fibre, which drives the conversion cost. Edge cloud related CAPEX elements that have been considered are:

a) processing servers, whose cost is relatively low compared to 11-year CAPEX because they have just started their life-cycle, and their cabinets

b) setting up new equipment rooms at existing edge cloud sites - we assumed that edge cloud sites already exist in the simulation area, for example we considered 3rd party fixed telecoms exchanges as such existing sites
c) transport upgrades towards the network core
d) labour

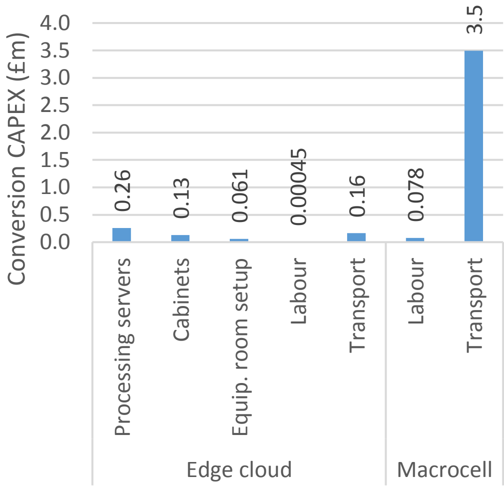



**Figure 3-7: Conversion CAPEX**

This conversion cost is not included in our TCO analysis between 2020 and 2030 to allow for a like for like comparison of the on-going CAPEX and OPEX of the two network options as they evolve over time to be made. However, these conversion costs clearly need to be noted when assessing in particular, the short-term risks associated with migration to 5G NORMA like virtualised networks.

Note that as part of the conversion-cost incurred before 2020, the transport in C-RAN configuration is upgraded to dark fibre during the conversion due to increased data rate requirement with respect to D-RAN transport requirements. In comparison, with D-RAN configuration the transport upgrade to dark fibre CAPEX is incurred during the study period once traffic grows and antenna site transmission bandwidth requirements reach a point where dark fibre is more cost effective than a managed service product (in terms of 10-year TCO with dark fibre having a high CAPEX but low OPEX whereas managed services then to have a lower initial CAPEX but high on-going OPEX particularly as bandwidth requirements grow). For C-RAN this CAPEX is incurred before the start of the period. This explains why the D-RAN transport is slightly higher than that of C-RAN. The aggregate view of CAPEX of Figure 3-6 across the simulation period is Figure 3-1 where the difference in transport CAPEX accounts for 1.4% of C-RAN TCO.

#### 3.1.1.3 OPEX results

Figure 3-8 shows the evolution of OPEX over time. Macrocell OPEX dominates in both C-RAN and D-RAN configurations. The OPEX of the macrocell antenna sites is lower with C-RAN than with D-RAN because of the reduced equipment needed for a RRH with C-RAN compared with the case of D-RAN with a full basestation also included at the macrocell antenna site which results in lower site visit and software licensing and maintenance costs at C-RAN macrocell antenna sites. Similarly, to the observation in CAPEX, the edge cloud site OPEX also grows more significant over time. This is due to the capacity of traffic to be processed at the edge cloud sites growing over time and requiring more servers, cabinets and floor space.

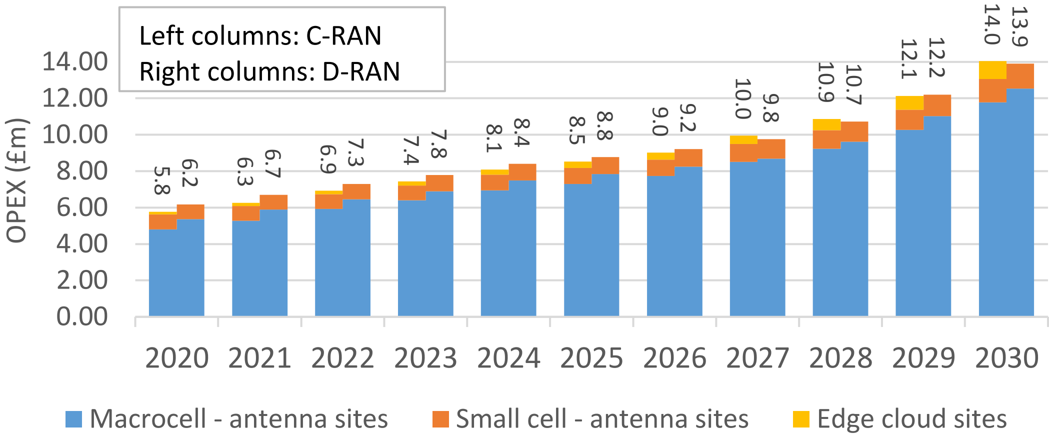



**Figure 3-8: OPEX over time**

Figure 3-9 shows the OPEX breakdown of macrocell antenna sites for C-RAN. The major cost drivers are the site rental and the energy consumption.

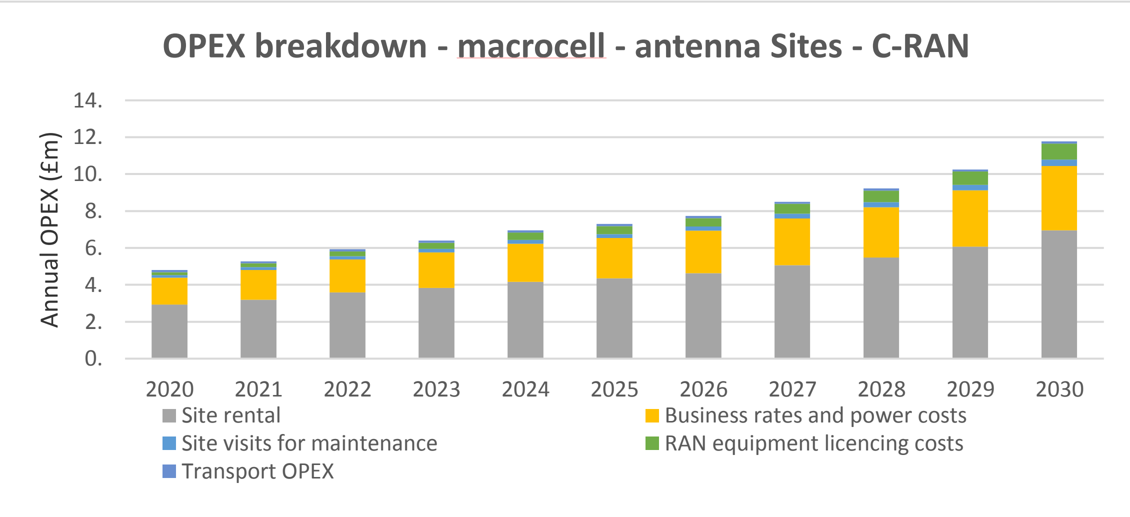



**Figure 3-9: OPEX breakdown of macrocell antenna sites for C-RAN**

## 3.1.2 Sensitivity Analysis

The sensitivity analysis was conducted by flexing the following input parameters: traffic volume, transport cost, and edge cloud cost.

### 3.1.2.1 Traffic volume

The effect of traffic evolution on the total cost is described in this section. The baseline value is traffic volume growth with 30% CAGR which is the medium case referred to earlier. For the sensitivity analysis values of 20 and 40% CAGR were investigated. Note these are different to the low and high traffic volume scenarios discussed in Section 2.3.3 which are used in the business case analysis in Chapter 4. Figure 3-10 shows how the cost changes for D-RAN and C-RAN for three variations of traffic volume growth. Table 3-2 summarises the cost reduction of C-RAN when compared against D-RAN.

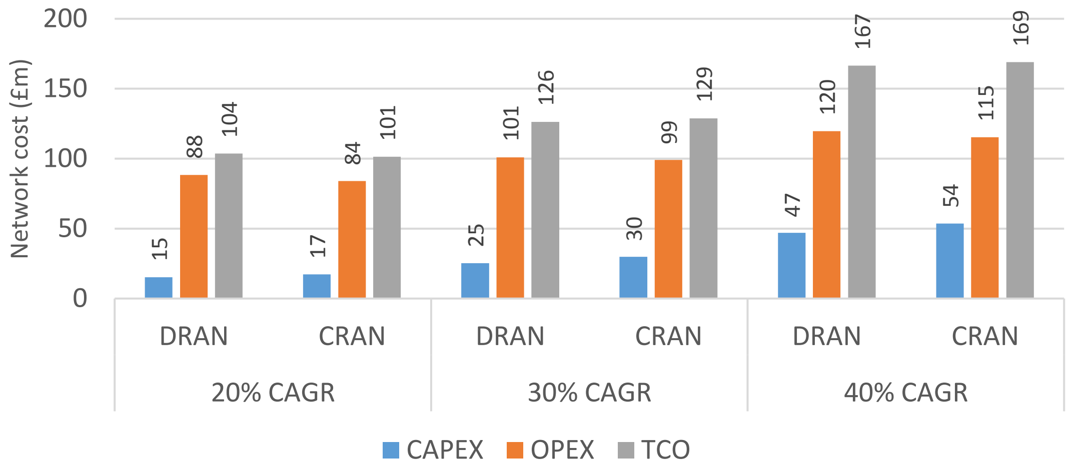



**Figure 3-10: Effect of traffic evolution on costs**

Resonating the trend from the baseline growth of 30%, C-RAN CAPEX is higher than that of D-RAN whereas C-RAN OPEX is lower than that of D-RAN, and in effect variations in TCO between the two configurations are balanced. For eMBB, one tenant and regardless of traffic volume growth virtualisation TCO penalties are marginal.

With increasing traffic volume growth, CAPEX increases exponentially whereas OPEX grows linearly. This is like to be due to the number and specifications of the new sites. As the demand growth increases, more new sites with higher specifications (antennas with more elements, additional frequency bands) are needed and this ushers the exponential increase in CAPEX. On the other hand, OPEX grows almost linearly with the number of macrocell antenna sites and site configurations.

In the case of the baseline demand volume growth of 20% CAGR, C-RAN TCO was found to be about 2% greater than that of D-RAN, see the analysis above. With higher demand growth there is higher utilisation of edge cloud sites, and this makes C-RAN more expensive compared to D-RAN, see Section 2.4.5. On the other hand, higher economies of scale due to higher utilised cabinets on the edge cloud sites balances the slight increase of additional servers brought about from higher spectrum utilisation. With lower demand growth there is lower utilisation of edge cloud sites, and this makes C-RAN less expensive compared to D-RAN, see Section 2.4.5.

Note that as all of the traffic scenarios investigated start from the same 2020 traffic level and then diverge from 2020 onwards the initial C-RAN conversion costs reported earlier are not impacted by this sensitivity analysis.

**Table 3-2: Effect of traffic growth on D-RAN and C-RAN configurations. Baseline growth is 30% CAGR.**

| | D-RAN (£m) | | | C-RAN (£m) | | | Cost savings of C-RAN compared to D-RAN | | |
|---|---|---|---|---|---|---|---|---|---|
| | **20%** | **30%** | **40%** | **20%** | **30%** | **40%** | **20%** | **30%** | **40%** |
| **CAPEX** | 15.2 | 25.3 | 46.9 | 17.3 | 29.8 | 53.6 | -13.3% | -17.7% | -14.2% |
| **OPEX** | 88.4 | 101 | 120 | 84.0 | 99.0 | 115 | 5.0% | 2.0% | 3.6% |
| **TCO** | 104 | 126 | 167 | 101 | 129 | 169 | 2.3% | -2.0% | -1.4% |

### 3.1.2.2 Transport costs

The transport costs were varied between a low case, medium (baseline) and a high case, and its effect on TCO was studied. More specifically, the values of the following parameters were varied: dark fibre CAPEX and OPEX, and Ethernet Access Direct (EAD) (i.e. managed fibre) CAPEX and OPEX. Table 3-3 summarises the low/baseline/high cost assumptions.

**Table 3-3: Low/baseline/high cost assumptions for transport cost sensitivity analysis**

| Type | CAPEX (£k) | OPEX (£k) |
|---|---|---|
| **Dark Fibre (1 Gbit/s)** | 31.9 (low 15.95, high 63.8) | 1.125 (low 0.56, high 2.25) |
| **Dark Fibre (10 Gbit/s)** | 33 (low 16.5, high 66) | 1.125 (low 0.56, high 2.25) |
| **Dark Fibre (100 Gbit/s)** | 35.5 (low 17.75, high 71) | 1.125 (low 0.56, high 2.25) |
| **Ethernet Access Direct (EAD) 1 Managed (1 Gbit/s)** | 2.1 | 3.15 |

To put the transport costs into perspective of their contribution towards 11-year TCO, the effect of virtualisation is, see Figure 3-1:

- macrocell transport CAPEX is unchanged
- macrocell transport OPEX decreases by 1.4%
- small cell transport decreases by 0.36%
- edge cloud transport is introduced with 0.01%

Transport cost accounts for 1.75% of TCO, therefore, variations in transport costs are expected to have limited effect on TCO. Table 3-4 shows the cost difference of C-RAN compared with D-RAN, for the low and high cases, as a result of the cost model. CRAN slightly benefits from lowered transport costs, although only in a very limited way because of transport's minor contribution to the TCO, which, as explained before, is dominated by site rental and energy costs (including business rates).

**Table 3-4: Effect of transport cost on D-RAN and C-RAN configurations**

| | D-RAN (£m) | | | C-RAN (£m) | | | Cost savings of C-RAN compared to D-RAN | | |
|---|---|---|---|---|---|---|---|---|---|
| | **Low** | **Base** | **High** | **Low** | **Base** | **High** | **Low** | **Base** | **High** |
| **CAPEX** | 23.1 | 25.3 | 28.4 | 29.2 | 29.8 | 32.6 | -26.7% | -17.7% | -14.7% |
| **OPEX** | 99.9 | 101 | 104 | 97.0 | 99.0 | 98.5 | 2.8% | 2.0% | 5.0% |
| **TCO** | 123 | 126 | 132 | 126 | 129 | 131 | -2.7% | -2.0% | 0.75% |

Figure 3-11 shows the C-RAN conversion CAPEX which is spent before 2020 (and not reported in the above TCO) to migrate the existing network from D-RAN to C-RAN. This additional CAPEX conversion-cost was calculated at £2.4m, £4.2m, and £7.8m for the low, baseline, and high cases, respectively. Halving and doubling the transport CAPEX assumption, as in low and high case respectively, is directly translated into similar response in transport upgrade CAPEX. This is because we assumed that the transport upgrade CAPEX from managed- to dark-fibre has a similar value to that of new dark-fibre.

Overall, the result from this sensitivity analysis shows that most of the conversion cost incurs due to macrocell transport upgrade, and that the edge cloud site setup cost is relatively small, due to few edge cloud sites and newly purchased servers. This is reinforced by the sensitivity analysis in Section 3.1.2.3 which flexes edge cloud site costs and shows little impact on the C-RAN conversion costs.

Regardless of the transport setting, macrocell transport upgrade remains the major driver of the conversion cost. In the low case, representing an operator with access to their own existing fibre-network, the conversion costs are significantly reduced and nearly halved. In the high case, representing a city which lacks readily available fibre, the conversion cost is nearly doubled and potentially a barrier for transition. This shows the importance of access at least to fibre ducts if not dark fibre in areas that are considered prime candidates for migration to virtualised networks like the smart city scenario explored here. This is discussed more in Section 6.1.3, under implications for governments and regulators. It also shows that these C-RAN conversion costs will vary greatly depending on the existing infrastructure and access to fibre that an MNO might have which will vary between MNOs with a legacy in providing fixed telecoms networks as opposed to those who are purely mobile network providers.

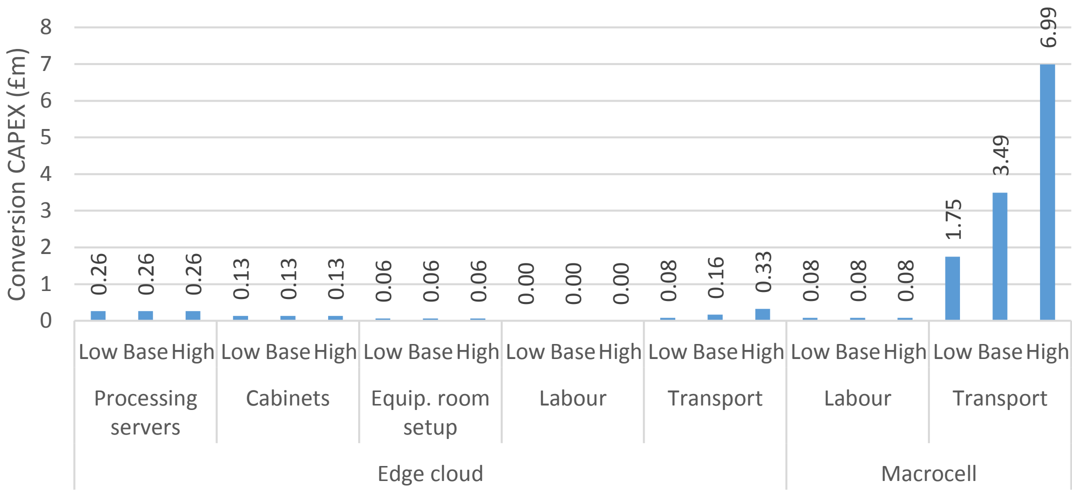



**Figure 3-11: Conversion CAPEX**

**Table 3-5: Impact on the cost of converting existing sites from D-RAN to C-RAN**

| | Low | Medium | High |
|---|---|---|---|
| **CAPEX C-RAN conversion costs (£m) for 130 macrocells with 6 edge cloud sites** | £2.4m | £4.2m | £7.8m |
| **Percentage of 2018 total annual network expenditure for D-RAN spent on C-RAN upgrade in 2019** | 35% | 62% | 117% |

#### 3.1.2.3 Edge Cloud Costs

The edge cloud cost was varied between a low case and a high case, and its effect on TCO was studied. Table 3-6 shows the input values for the three cases of low, medium and high. The CAPEX, OPEX and TCO results of the comparison are shown in Table 3-7.

To put these edge cloud cost variations into perspective of 11-year TCO, the effect of virtualisation is, see Figure 3-1:

- Processing server CAPEX is introduced with 4.4%
- Cabinet CAPEX is introduced with 0.5%
- Cabinet rent and utilities is introduced with 1.4%
- Operating overhead is introduced with 0.42%

The edge-cloud cost-elements that are varied in this section account for 6.72% of TCO, therefore, variations of these costs are expected to have limited effect on TCO. It is reminded that Section 2.4.4 analysed the cost of virtualisation and concluded that server CAPEX for end-of-life cycle reduces cost benefits of virtualisation.

Table 3-7 shows the cost difference of C-RAN minus that of D-RAN, for the low and high cases, as a result of the cost model. It appears that the cost model reacted to the cost difference as expected; increasing server CAPEX (high case) reinforced the cost penalties of virtualisation, whereas decreasing server CAPEX (low case) reversed them. Note that the result in TCO variation is subdued when compared to the level of input variation. This is explained when considering that the cost model can shift (low-velocity) traffic between small- and macro-cell layers, which acts as a degree of freedom in counter balancing the input change. In this particular example, increasing server CAPEX (high case) would be translated into the small cell layer becoming more attractive, compared to the baseline case, which explains why the output TCO did not vary as much as 6.72% of the above analysis. For the low case, the TCO reduction is 1.0%, whereas for the high case it is -2.3%.

**Table 3-6: Assumptions for the definition of Edge Cloud Sites**

(a)

| Metric | Cost (£) | Comment |
|---|---|---|
| Fixed costs to set up an installation at edge cloud site | 10,100 medium<br>5,050 low<br>20,200 high | Initial CAPEX incurred to set up new edge cloud sites. Based on RW estimate for setting up a baseband unit hotel and local loop unbundling (LLU) costs for metering and site visit and interpreted for a 5G NORMA based architecture.<br>Costs include: power supply distribution boards, sockets, lighting, enclosure, overhead racking and cabling. |
| Fixed costs to set up a cabinet/rack at the edge cloud site | 21,400 medium<br>10,700 low<br>42,800 high | CAPEX to set up cabinet at edge cloud site. Incurred for each new edge cloud site and each time an upgrade takes the number of cores beyond the capacity of a cabinet (i.e. multiples of 256 cores).<br>Includes power distribution, air conditioning set-up, space set-up, AC distribution and cabinet. |
| Fixed costs per server | 6,500 (Unvaried across all 3 cases) | Maximum of 16 servers per cabinet. Assumes 35% discount. This is equivalent to just under £500/installed core |

(b)

| | Rent and utilities / cabinet | Overhead of running each edge cloud site (including vendor services) | Licensing and Maintenance (£k) |
|---|---|---|---|
| Edge cloud/aggregation site | £6.6k per cabinet includes peak to average power use, rental and service charge, security and working practices audit (assumed annual), standby power / cabinet, power connection (rental) and electricity use. | £6.3k (includes £3.2k per site one-off charge per site visit for vendor services) | 10% of active equipment (RF front end and baseband equipment where baseband is the processing on the edge cloud site rather than antenna site) of macrocells |
| Low | £3.3k | £3.15k | Not varied from above |
| High | £13.2k | £12.6k | Not varied from above |

**Table 3-7: Effect of varying edge cloud site elements, to represent different levels of access to suitable site locations, on D-RAN and C-RAN configurations**

| | D-RAN (£m) | C-RAN (£m) | | | Cost savings of C-RAN compared to D-RAN | | |
|---|---|---|---|---|---|---|---|
| | | Low | Base | High | Low | Base | High |
| **CAPEX** | 25.3 | 29.8 | 29.8 | 30.4 | -17.7% | -17.7% | -20.2% |
| **OPEX** | 101 | 97.7 | 99.0 | 101 | 3.3% | 2.0% | -0.3% |
| **TCO** | 126 | 127 | 129 | 132 | -0.9% | -2.0% | -4.3% |

Figure 3-12 shows the C-RAN conversion CAPEX which is spent before 2020 to migrate the existing network from D-RAN. This additional CAPEX conversion-cost was calculated at £4.1m,

£4.2m, and £4.4m for the low, baseline, and high cases, respectively. Halving and doubling the cabinet and equipment-room setup CAPEX assumption, as in low and high case respectively, is directly translated into similar response of these elements in the conversion CAPEX. However, because these elements are a small proportion of the conversion CAPEX (which is driven by transport costs as shown in the previous section), the latter is practically unaffected by the variation considered in this sensitivity analysis.

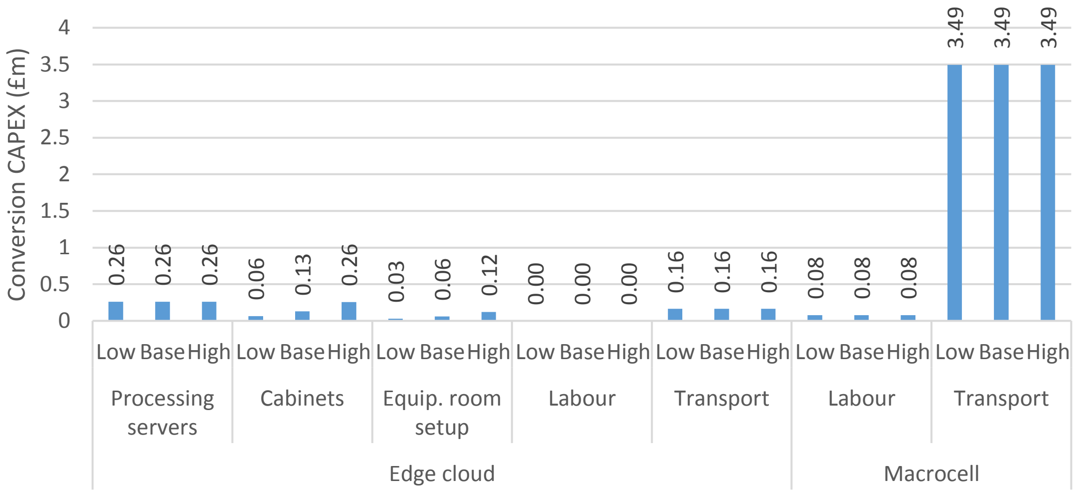



**Figure 3-12: Conversion CAPEX**

### 3.1.3 Conclusions

To assess the cost of virtualisation we simulated a network with D-RAN configuration from 2020 to 2030, and a network with C-RAN in the same time frame. Both networks had similar initial states – the conversion to C-RAN was assumed to be done in 2019 – and they were allowed to evolve per year in the most economical fashion based on a present value TCO optimiser, see Section 2.4.1. We compared TCO, CAPEX and OPEX between the two networks.

When viewed from a cost aspect network virtualisation is in effect a shift from macrocell to edge cloud expenditure, with balanced dynamics between savings in the former and additional costs in the latter. Isolating the view in CAPEX, investment in processing servers at the edge cloud sites replace the bare metal base band. However, due to relatively fast end-of-life cycles at the edge cloud, diminishing advances in core capabilities and 11-year flat server cost with time, C-RAN CAPEX appears to be in excess of that of D-RAN configuration. On the other hand, virtualisation results in reduction of OPEX, so that in effect there is no practical cost penalty in C-RAN over D-RAN (in terms of on-going CAPEX and OPEX after initial conversion costs have been incurred).

With the baseline parameters, TCO of C-RAN configuration was calculated 2% greater than that of D-RAN, however we note that changing the assumptions on end-of-life cycle, server capabilities will affect this result. In broad terms, we found that the cost of virtualisation remains in practice trivial, in all sensitivity analyses conducted. This is because virtualisation tends to impact processing costs, site transport costs, and edge cloud site costs which are not large components of the 11-year TCO compared to site rental and RF front end equipment costs which remain the same between C-RAN and D-RAN.

The cost of virtualisation remains in practice trivial regardless of the traffic forecast growth, cost of transport elements, or cost of edge cloud sites, for the examined ranges. Overall, given the minor differences between TCO, which are up to ±3%, it cannot be concluded that the cost of C-RAN is in general higher or lower than that of D-RAN. Nevertheless, a virtualised C-RAN infrastructure has its benefits in view of flexibility and programmability required for a forced introduction of novel services and/or network slice types.

## 3.2 Value of multi-tenancy

This section describes Evaluation Case 2 which is the cost comparison between a network that features multi tenancy – such a network serves the demand of multiple tenants and potentially multiple MSPs via a shared infrastructure set rather than separate ones – compared to one that does not, with key assumptions regarding the study area definition, cost assumptions and network dimensioning already given in Chapter 2. In both cases C-RAN networks are assumed and the 2017 existing infrastructure for initially two MNOs (based on two typical site portfolios publicly reported in the study area as discussed in Section 2.4.2) are densified to support eMBB traffic growth out to 2020. Up to 2020 each infrastructure set is assumed to be not shared and dedicated to one MNO only. Beyond 2020 the impact of both MNOs using a shared infrastructure set is examined. The shared elements are spectrum carriers, tower/masts and antennas, RRHs, edge clouds and backhaul/transport. From the start of 2020 onwards, existing sites become multi-tenant, i.e. they can serve demand from the tenants and end users of either MNO. As described in Chapter 2.2.2, this sharing of infrastructure amongst existing MNOs could be realized as a single new MSP created to implement the virtual network functions required per service and provide services to the existing MNOs and their users who become tenants of the MSP. If the MNO would like to maintain more control over their network implementation it is alternatively possible to realise two MSPs using the same shared infrastructure set. In this section, we present results using the terminology of a single MSP serving two tenants but the results are also applicable in the case of maintaining two MSPs with greater control over network implementation each. Note only macrocell antenna sites can be shared in this scenario as small cells are assumed to be D-RAN and not shared.

The section finishes with the sensitivity analysis, where the following three parameters are flexed: traffic evolution, cost of various CAPEX and OPEX parameters, and different number of tenants.

Note that there are network costs associated with the necessary activity to create a shared infrastructure set, such as network consolidation, site decommissioning, and macrocell integration. These costs have not been considered in this study. Also, while some site sharing is already implemented today we assume in the non-sharing case that no sites are shared between the two MNOs to simplify our analysis and show the difference between the two extremes no sharing at all vs. complete multi-tenancy.

### 3.2.1 Baseline case

#### 3.2.1.1 TCO results

In this section, we show the major cost drivers and a comparison between the TCO of a network with two tenants – an MSP that has SLA with two InP and offers services to two tenants – compared to the sum of TCO of two independent single-tenant networks – two MNO. In both cases the 11-year TCO has been partitioned into the cost drivers shown in Figure 3-13. The inner circles show the three network elements employed in the analysis: macrocells, small cells and edge cloud sites. The intermediate and external circles show the CAPEX and OPEX components. The annotated percentages and dimensions of the pie-slices of both graphs are relative to the sum of TCO of the two MNO, so that direct comparisons between the percentages on these two graphs are possible.

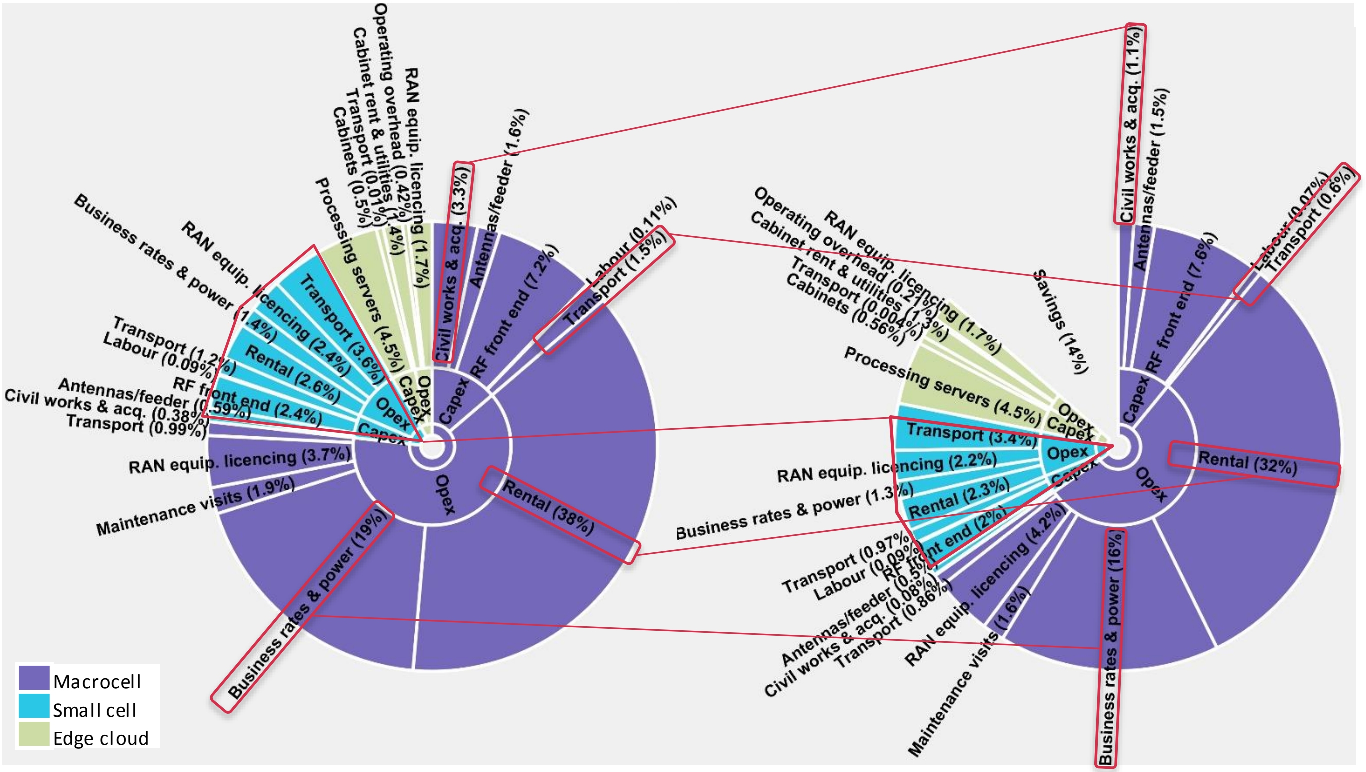



**Figure 3-13: Cost components affected by sharing. The sum of two MNO that own independent infrastructure (left), and an MSP that serves the demand of two tenants via sharing network resources and equipment across two infrastructure providers (right).**

Savings from sharing are greater in macrocell OPEX. This is because OPEX is accrued over 11 years and applies to existing & new sites alike, compared to CAPEX which occurs once per new macrocell or upgrade. The greatest saving from multitenancy arises from sharing macrocell site rental and business rates & power with 6% and 3% saved, respectively. This is due to the reduced number of sites needed under a shared network.

Savings are also observed in macrocell CAPEX. The MSP with two tenants spends 3% less on macrocell civil works & acquisition and in their transport towards the edge cloud. These savings would be greater if the small cells were shared as well as macrocells. In the shared network single MSP cost-estimation, the macrocells become more attractive compared to small cells because the former can support twice the spectrum holdings with the same civil works and acquisition cost. As a result, the cost-model invests more on macrocells in the multi-tenancy case, thus the relatively small saving in civil works & acquisition. The same argument – macrocells are shared and small cells are not, thereby favouring invest in macrocells over small cells – also explains the reason MSP benefits from 2% saving in the small cell layer, since less of them are commissioned.

Expenditure at the edge cloud is unaffected by multi-tenancy. This is expected as sharing antennas sites does not affect processing-server dimensioning.

The total network expenditure per year for a network that features multi tenancy and for the corresponding pair of individual networks are shown in Figure 3-14. In all the years TCO of a multi-tenant network is lower than the sum of two individual-network TCO. The cost savings achieved by means of multi tenancy are described in Table 3-8; CAPEX (23 % of TCO) and OPEX (77% of TCO) reductions are 15.7% and 12.9%, respectively, which leads to TCO reduction of 13.6%.

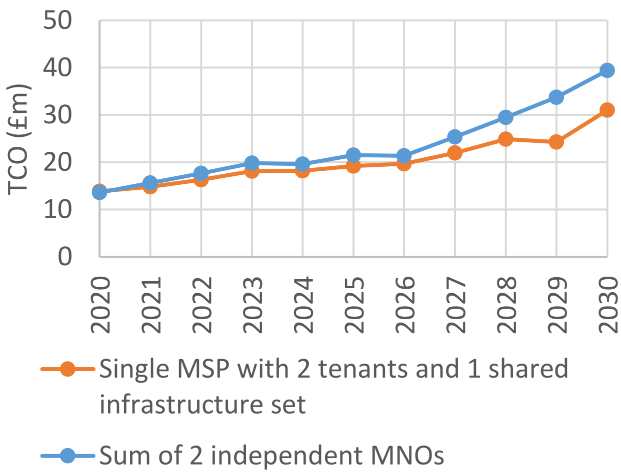


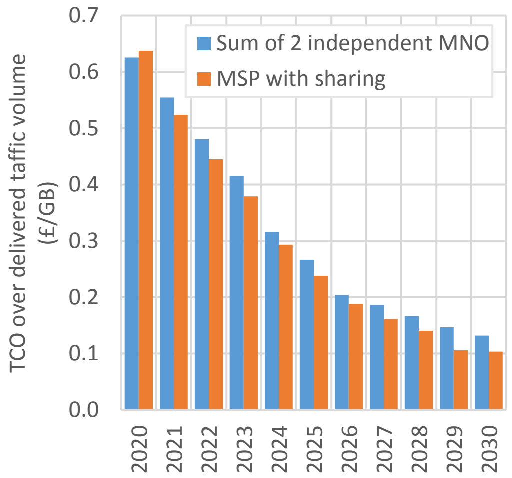

**Figure 3-14: TCO per year for a network that features multi tenancy and sum of TCO of two networks that do not**

**Table 3-8: Comparison of costs of shared vs. separate infrastructure, period 2020-2030**

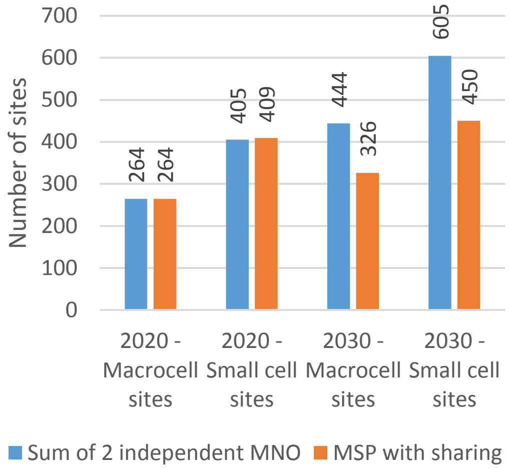
| | Sum of 2 independent MNO (£m) | MSP with sharing (£m) | Cost savings of an MSP with sharing |
|---|---|---|---|
| CAPEX | 60.1 | 50.6 | 15.7% |
| OPEX | 197 | 172 | 12.9% |
| TCO | 257 | 222 | 13.6% |

Note that our analysis does not include decommissioning and consolidation of the site portfolios from the two infrastructure sets being merged from 2020 onwards. This would potentially deliver further OPEX savings earlier than shown in the analysis here due to reduced site numbers but at the cost of visiting and de-commissioning existing sites. The other extreme is shown in our sensitivity analysis in Section 3.1.2 where the benefits of multi-tenancy appear earlier in the study period if a new joint infrastructure set is deployed initially rather than working from consolidating two existing site portfolios.

The evolution of the cost per GB for the two cases, with and without multi-tenancy, is depicted in Figure 3-15 (a), where there is a cost reduction of about 6 times over the 11-year period examined. The number of macrocell antenna sites and small cells for both cases, with and without multi-tenancy, appear in Figure 3-15 (b).




(a) Evolution of TCO over delivered traffic volume




(b) Number of antenna sites for 1 MSP (2 tenants, 1 shared infrastructure set), compared against the sum of 2 independent MNO, at the end of 2020 and 2030

**Figure 3-15: Evolution of TCO over delivered traffic volume and evolution of network size**

In both cases, there is a significant increase in the number of network elements, antenna sites and consequently edge cloud servers. The two simulated cases correspond to networks that evolve independently from the start of 2020, thus at the end of 2020 we observe similar number of macrocells and small cells in the two cases. However, in 2030, the number of macrocells and small cells is higher in the case of the two independent MNO compared to the MSP-with-sharing case. This is because from the start of 2020 the MSP has the advantage of spectrum-pooling within new macrocell installations and upgrades which gives double the capacity of the sites in the non-sharing case to serve the joint-demand.

Figure 3-16 shows the breakdown of the sites at the end of each modelled year. For each year there are two columns, denoted with A for the sum of 2 independent MNO and with B for the single MSP with 2 tenants and 1 shared infrastructure set. Solid fills represent macrocell site and patterned small cell site counts. Each colour corresponds to an antenna site specification, a number of antennas and bandwidth at each modelled band. Note that the spectrum pool options are only available to the MSP, for example 80 MHz at 1.8 to 2.6 GHz or 210 MHz in total are only available to the MSP. Spectrum pooling gives the MSP the cost advantage over the independent MNO. We also note that, even though pooled-resource macrocells are available as an option to the MSP, the cost-benefit optimiser chooses to make use of them only when that makes financial sense. It is reminded that pooling of network resources results in additional edge cloud processing costs.

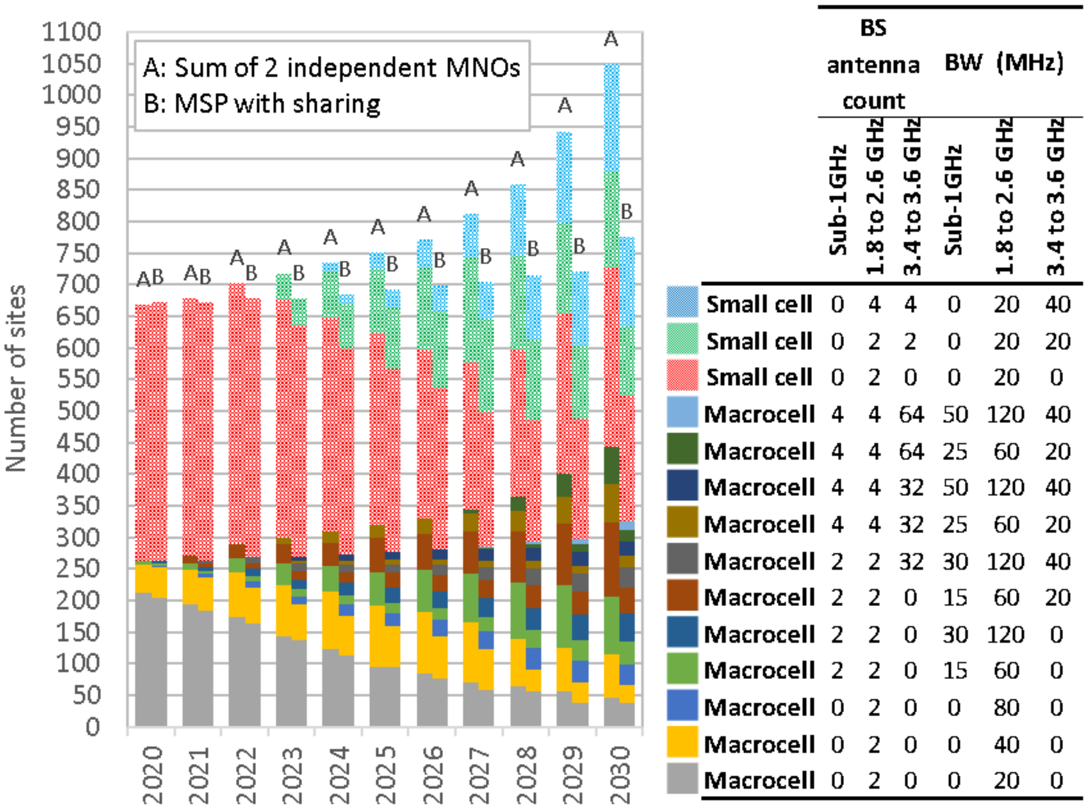



**Figure 3-16: Number of sites to serve the demand each modelled year**

#### 3.2.1.2 CAPEX results

The CAPEX breakdown is provided in Figure 3-17. The majority of costs correspond to the macrocell layer for both cases, with and without multi-tenancy. In most years the MSP CAPEX is lower than the case without multitenancy, because of the lower number of macro- and small cell sites that are needed when infrastructure is shared. The cost difference between the two cases increases from 2027 onwards because the capacity of all available frequency bands on sites in peak demand hotspots gets exhausted and a site densification is needed. This can be done more efficiently without so much duplication and overlap of the coverage areas of site portfolios in the shared case compared with when the two MSPs are densifying their networks independently.

#### 3.2.1.3 OPEX results

The OPEX breakdown is shown in Figure 3-18. The majority of costs correspond to the macrocell layer. In all years the MSP OPEX is lower than the case without multitenancy because fewer macrocells are required but equipped with more bandwidth. In the multitenancy case fewer small cells are required because the resource-pooling and hence higher capacity advantage of macrocells renders small cells less attractive.

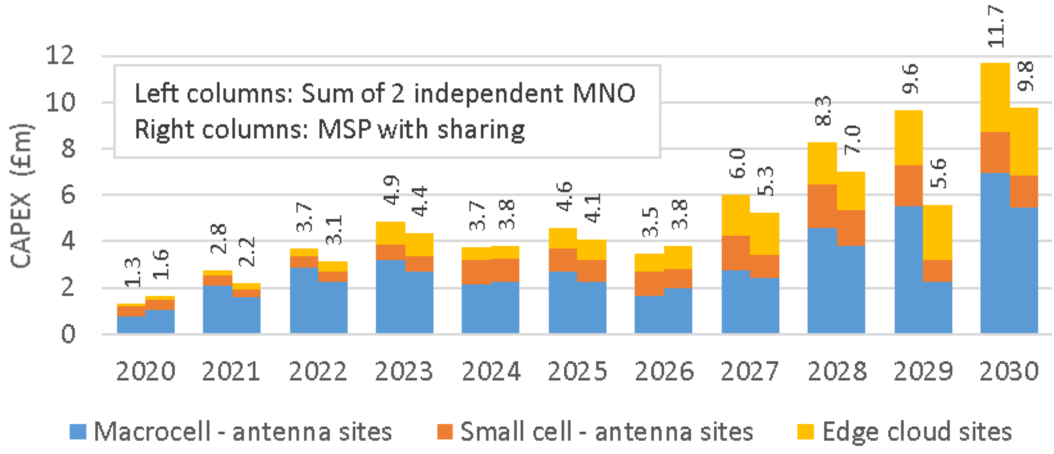



**Figure 3-17: CAPEX composition. Single MSP with 2 tenants and 1 shared infrastructure set on the right; sum of 2 independent MNO on the left.**

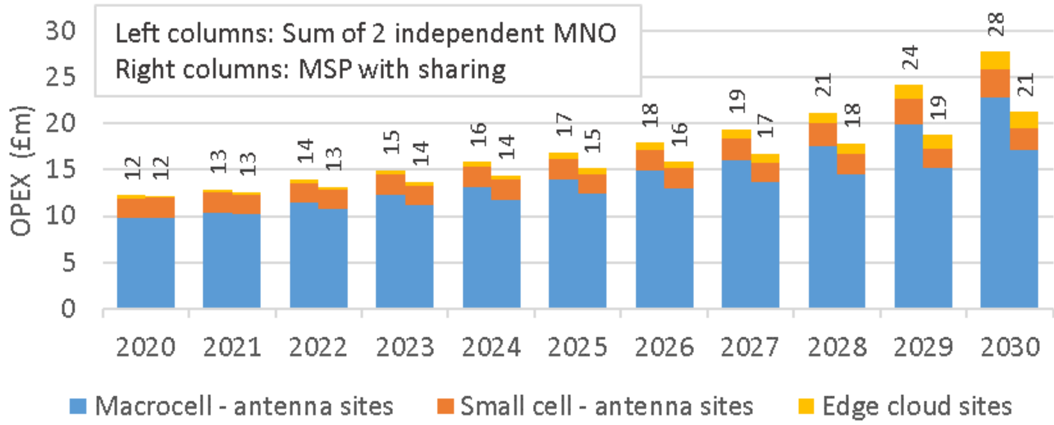



**Figure 3-18: OPEX per year. Single MSP with 2 tenants and 1 shared infrastructure set on the right; sum of 2 independent MNO on the left.**

### 3.2.2 Sensitivity Analysis

The sensitivity analysis was performed with three types of input values: traffic, CAPEX and OPEX parameters, and number of MSPs.

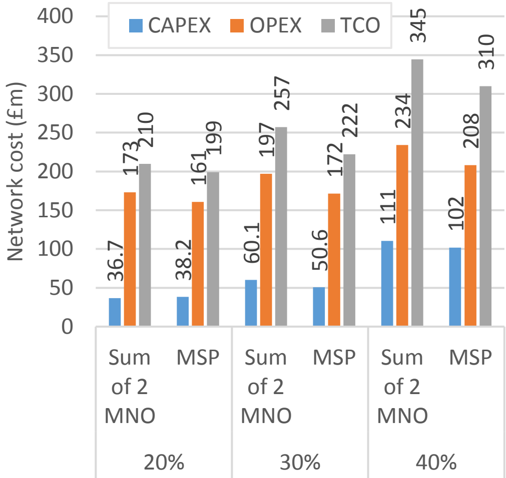
#### 3.2.2.1 Traffic volume

The effect of traffic evolution on the total cost is described in this section. The baseline value is traffic volume growth with 30% CAGR, and for the sensitivity analysis values of 20 and 40% CAGR were investigated. Note these are different to the low and high traffic volume scenarios discussed in Section 2.3.3 which are used in the business case analysis in Chapter 4. Figure 3-19(a) shows how the cost changes for the two cases, with and without multi-tenancy, for three variations of traffic volume growth.

With increasing traffic volume growth CAPEX, OPEX and TCO increase in both cases. The TCO of the single MSP with 2 tenants and 1 shared infrastructure set is lower than the TCO of the sum of the 2 independent MNO, regardless of traffic-volume growth-rate. We note that for growth of 20% CAGR the MSP CAPEX is slightly higher than that of the 2 MNO – the difference is 4.0% additional CAPEX in the MSP case which is offset by reduced OPEX – which occurs because the MSP invests on higher-cost shared- macrocell antenna sites.

Figure 3-19 (b) shows the cost savings achieved with multitenancy for variable traffic-volume growth-rates. The key observation is that with a decreased growth rate benefits from multitenancy are reduced. This is in alignment with expectations because multitenancy cost-savings materialise in our scenario when network densification is needed and this can be fulfilled by high capacity shared macrocell antenna sites making use of the spectrum-pooling, which consequently results in rent, business rates and power OPEX savings. With subdued demand hotspots in the network the requirement to densify occurs less often and multitenancy has less opportunities. Note we do not model consolidation of the site portfolios and site decommissioning in areas of significant coverage overlap but more moderate demand where a single site from one of the existing portfolios would be sufficient to serve demand from both MSPs. This would improve the savings achieved via multi-tenancy in lower demand areas such as more rural and suburban areas not examined in this study where sharing of networks is already implemented in some cases today.

With an increased growth rate benefits from multitenancy are maintained when viewed in absolute terms, where £35m is saved in both 30 and 40% rates. It appears that higher traffic-volume growth-rates result in similar macrocell antenna site volumes compared to the baseline and the additional demand is served by the small cell layer due to reaching limitations on macrocell densification. It is reminded that small cells do not support multitenancy.




(a) TCO in absolute values

| | 20% | 30% | 40% |
|---|---|---|---|
| **CAPEX** | -4.0% | 15.7% | 8.0% |
| **OPEX** | 7.0% | 12.9% | 11.0% |
| **TCO** | 5.1% | 13.6% | 10.0% |

(b) TCO savings achieved by transitioning to a single MSP with two tenants and one shared infrastructure set as a percentage of the sum of TCO of two independent MNO

**Figure 3-19: Effect of traffic demand growth on TCO for a single MSP with two tenants and one shared infrastructure set, compared against the sum of two independent MNO. Baseline growth is 30% CAGR.**

#### 3.2.2.2 CAPEX and OPEX parameters

Several CAPEX and OPEX parameters were varied between a low case, medium (baseline) and a high case to understand the potential impact on the benefits of multi-tenancy in other city locations other than central London. Table 3-9 summarises the CAPEX and OPEX parameters that were varied. Only macrocell antenna site costs were varied as:

- Small cell cost elements are small compared with macrocell antenna site costs in terms of contribution to TCO in the study period.
- Edge cloud site cost variation are not considered here as they have already been examined in Evaluation Case 1 and were not found to have significant impact on the TCO as they are not a large cost element compared with macrocell antenna sites. Also, these costs would not change by city location but rather operator scenario.

**Table 3-9: Parameters employed for the sensitivity analysis**

| | Baseline | Low | High | Comments |
|---|---|---|---|---|
| Macro site acquisition and civil works | £46,200 | £41,500 | £50,820 | Assumed 10% of this cost element is site acquisition. Varied this 10% from a marginal cost of £80 (for cases where site acquisition is extremely straightforward i.e. part of an existing arrangement) to £9240 i.e. double our baseline assumption. |
| Macrocell antenna site rent | £20k pa | £10k pa | £40k pa | Half and double |
| Macrocell antenna site business rates[8] and power | £10k pa | £2.5k pa | £20k pa | Business rates are approx. 75% of the baseline £10k value. Thus in other countries with no business rates this OPEX item could be as little as £2.5k. In high case we doubled the baseline value. |

To put these cost elements into perspective of their contribution towards 11-year TCO, the effect of multitenancy is, see Figure 3-13:

- macrocell civil works and acquisition decreases by 2.2%
- macrocell rent decreases by 6%
- macrocell business rates & power decreases by 3%

Overall, these cost elements account for 11% of TCO and the majority is attributed to OPEX. It is unclear how their variation will affect the multitenancy benefit, because their variation affects both cases, with and without multi-tenancy. The option to offset the additional cost with investment in the small cell layer is also another method of balancing network costs.

Table 3-10 shows the cost savings achieved with multitenancy. Compared against the baseline, the reduction of OPEX leads to:

- reduction in OPEX in both cases, with and without multi-tenancy
- similar CAPEX in both cases, with and without multi-tenancy, because the reduction in OPEX does not affect the need for network expansion
- reduction in TCO in both cases, with and without multi-tenancy, because OPEX is reduced and CAPEX remains unchanged
- in relative terms, OPEX becomes a smaller component of TCO and its associated benefit in sharing is diminished

in relative terms, CAPEX becomes a greater component of TCO and its associated benefit in sharing is increased
in relative terms, TCO is practically unaffected

Compared against the baseline, the increase of OPEX leads to:

- increase in OPEX in both cases, with and without multi-tenancy, and the cost-optimiser deploys more small cells because they become highly competitive against the expensive macrocells
- similar CAPEX in both cases, with and without multi-tenancy, because the increase in OPEX does not affect the need for network expansion
- increase in TCO in both cases, with and without multi-tenancy, because OPEX is increased and CAPEX remains unchanged
- in relative terms, OPEX becomes a greater component of TCO but the cost-optimiser deploys less macrocells to offset the increased running-costs and its associated benefit in sharing is diminished because small cells are not shared

[8] Business rates are a tax applied to non-residential properties and are applied in the UK.

- in relative terms, CAPEX becomes a smaller component of TCO and its associated benefit in sharing is diminished
- in relative terms, benefits in TCO are subdued because of less reliance on the macrocell layer, which is where the opportunities for multitenancy exist

**Table 3-10: Cost reductions achieved with multitenancy, in absolute and percentage over the case without multitenancy**

| | Sum of 2 independent MNO (£m) | | | MSP with sharing (£m) | | | Cost savings of an MSP with sharing | | |
|---|---|---|---|---|---|---|---|---|---|
| | Low | Base | High | Low | Base | High | Low | Base | High |
| **CAPEX** | 60.8 | 60.1 | 58.9 | 49.2 | 50.6 | 51.5 | 19% | 15.7% | 13% |
| **OPEX** | 112 | 197 | 321 | 100 | 172 | 290 | 11% | 12.9% | 9% |
| **TCO** | 173 | 257 | 380 | 149 | 222 | 342 | 14% | 13.6% | 10% |

#### 3.2.2.3 Different Mobile Service Providers

The number of tenants that are served by the single MSP is varied between 2 (baseline), 3 and 4, and its effect on TCO was studied. More specifically, the cases that were examined were:

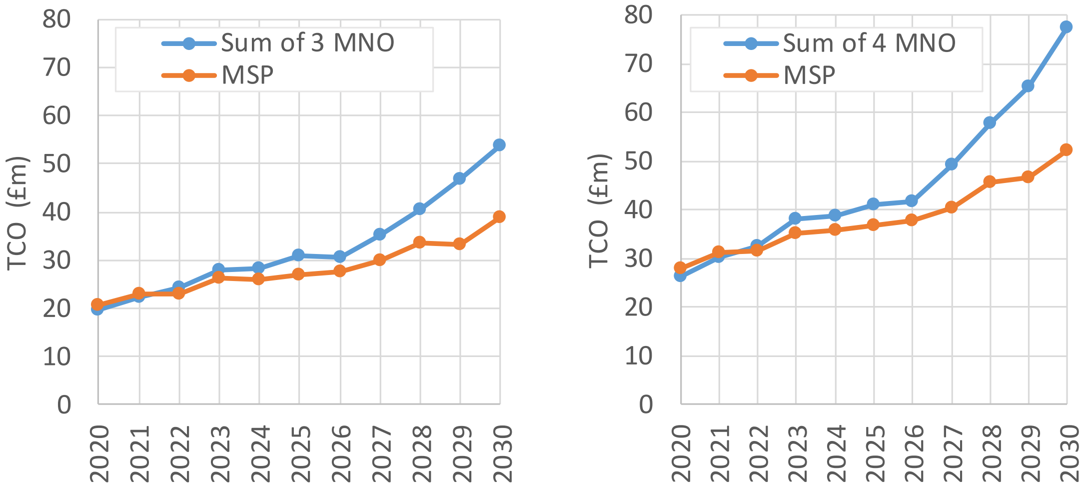
- Single MSP with 2 tenants and 1 shared infrastructure set that is a result of consolidating the infrastructure from 2 MNO, and maximum spectrum pooling of 210 MHz per macrocell
- Single MSP with 3 tenants and 1 shared infrastructure set that is a result of consolidating the infrastructure from 3 MNO, and maximum spectrum pooling of 210 MHz per macrocell
- Single MSP with 4 tenants and 1 shared infrastructure set that is a result of consolidating the infrastructure from 4 MNO, and maximum spectrum pooling of 210 MHz per macrocell

We limited spectrum pooling to 210 MHz per macrocell as per [5GN-D33].

As mentioned in Section 3.2.1.1 the cost-benefit of multitenancy is mainly due to the MSP having the advantage of spectrum-pooling within new macrocell installations and upgrades to serve the joint-demand. Spectrum-pooled macrocells can hold the demand from multiple tenants whereas macrocell rent, rates & power OPEX items are shared. We expect that

- the limitation of spectrum pooling to 210 MHz per macrocell to impede leaps from multitenancy of more than 2 tenants, and
- small trunking benefits may arise due to opportunities of better utilisation of infrastructure resources.

Figure 3-20 shows the TCO when a single MSP serves 3 or 4 tenants with 1 shared infrastructure set that is a result of consolidating the infrastructure from 3 or 4 MNO, respectively, and maximum spectrum pooling of 210 MHz per macrocell. Table 3-11 summarises CAPEX, OPEX and TCO savings achieved, and aligns with the above expectations.




(a) TCO when a single MSP serves 3 tenants with a single shared infrastructure set, compared to the sum of the TCO of 3 independent MNO

(b) TCO when a single MSP serves 4 tenants with a single shared infrastructure set, compared to the sum of the TCO of 4 independent MNO

**Figure 3-20: TCO for different number of tenants**

**Table 3-11: Cost savings when a single MSP serves 2 (baseline), 3 or 4 tenants with a single shared infrastructure set, compared to the sum of the TCO of 2, 3, or independent MNO, respectively**

| | Sum of multiple independent MNO (£m) | | | MSP with sharing (£m) | | | Cost savings of an MSP with sharing | | |
|---|---|---|---|---|---|---|---|---|---|
| | 2 MNO | 3 MNO | 4 MNO | 2 MNO | 3 MNO | 4 MNO | 2 MNO | 3 MNO | 4 MNO |
| **CAPEX** | 60.1 | 80.0 | 115 | 50.6 | 67.8 | 97.7 | 15.7% | 15.2% | 15.3% |
| **OPEX** | 197 | 280 | 383 | 171 | 241 | 323 | 12.9% | 14.0% | 15.6% |
| **TCO** | 257 | 360 | 498 | 222 | 309 | 421 | 13.6% | 14.3% | 15.5% |

### 3.2.3 Conclusions

To assess the cost benefit of multitenancy we simulated the networks of independent MNO from 2020 to 2030, and a network of a single MSP with multiple tenants and one infrastructure set in the same time frame. In the MSP case, the independent MNO networks were combined at the start of 2020 into a single infrastructure set, and thus were at the same state at that point in time. The networks were allowed to evolve per year in the most economical fashion based on a present value TCO optimiser. We compared TCO, CAPEX and OPEX between the networks, the sum TCO of the independent MNO against the TCO of the single MSP.

When viewed from a cost aspect multitenancy presents an opportunity to save on large OPEX cost elements such as macrocell rent, business rates and power. Savings originate predominantly from OPEX because it is accrued over 11 years and applies to existing & new sites alike, compared to CAPEX which occurs once per new macrocell or upgrade. Opportunities for savings materialise when the network makes use of the pooled spectrum resources ‘under the same roof’. New macrocell civil works and acquisition CAPEX is also saved, however this cost element is dwarfed by the 11-year accrued OPEX.

With the baseline parameters, multitenancy reduces the 11-year TCO by 13.6%. A greater reliance on the small cell layer reduces saving-opportunities from macrocell multitenancy, because small cells were assumed not to be shared. This is the case of a high traffic-volume growth-rate or if the macrocell OPEX were higher than that of the baseline, in which cases savings in TCO are reduced to 10%. Lack of traffic volume to necessitate utilisation of spectrum-pooled macrocells hampers TCO savings to 5%. Aggregating more tenants than two shows little benefit, TCO savings increase to 15.5% with 4 tenants, and multitenancy-benefits are limited due to the spectrum-pooling cap which was set at 210 MHz per macrocell.

## 3.3 Value of multi-service support

This section describes Evaluation Case 3 which is the cost comparison between a network with multiple slices (eMBB plus mMTC and/or uMTC) compared to one with a single slice (eMBB), with key assumptions regarding the study area definition, cost assumptions and network dimensioning already given in Chapter 2. In the case of eMBB an 18% market share is assumed but for all other services we assume a 100% market share for the study area (see Section 0). In both cases a virtualised C-RAN network configuration is assumed, and the 2017 existing infrastructure for an MNO is densified to support eMBB traffic growth out to 2020. This provides the ‘existing infrastructure for the MNO in 2020’. We then examine the evolution of and subsequent running costs for the period 2020-2030. The following cases have been assessed:

1. The network only caters for outdoor eMBB services for portable consumer devices
2. Semi-automated driving (uMTC, subset of V2I) has been introduced, in parallel to eMBB, and accommodated on any frequency band
3. Assisted driving basic (mMTC, subset of V2I) services have been introduced, in parallel to eMBB, and accommodated on any frequency band
4. Infotainment (eMBB, subset of V2I) services have been introduced, in parallel to eMBB, and accommodated on any frequency band
5. Smart meters (mMTC) services have been introduced, in parallel to eMBB, and accommodated on the sub-1GHz band
6. Smart meters (mMTC) services have been introduced, in parallel to eMBB, and accommodated on any frequency band

The smart meters were assumed to be situated indoors with building penetration loss of 15±8 dB.

In each case the model upgrades or deploys new sites to meet growing demand over time. Note that in Evaluation Case 3 the cost-optimiser’s search-radius was set to a greater value, because non-eMBB services typically have wider ranges compared to eMBB high datarate. A side-effect of the search-radius revision resulted in an ‘existing infrastructure for the MNO in 2020’ that differs slightly from that of eMBB-only cost analyses of evaluation cases 1 and 2, £ 130 vs 129 m in terms of 11-year TCO.

### 3.3.1 Baseline case

#### 3.3.1.1 TCO results

In this section we show the major cost drivers and a comparison between the TCO of a network with 1 slice (eMBB) and the TCO with 2 slices (eMBB plus smart meters served by sub-1GHz band). In both cases the 11-year TCO has been partitioned into the cost drivers shown in Figure 3-21. The inner circles show the three network elements employed in the analysis: macrocells, small cells and edge cloud sites. The intermediate and external circles show the CAPEX and OPEX components. The annotated percentages and dimensions of the pie-slices of both graphs are relative to the network with 2 slices, so that direct comparisons between the percentages on these two graphs are possible. The 2-slices support-premium that is not applicable to the eMBB-only network is marked on the graph as functionality gap.

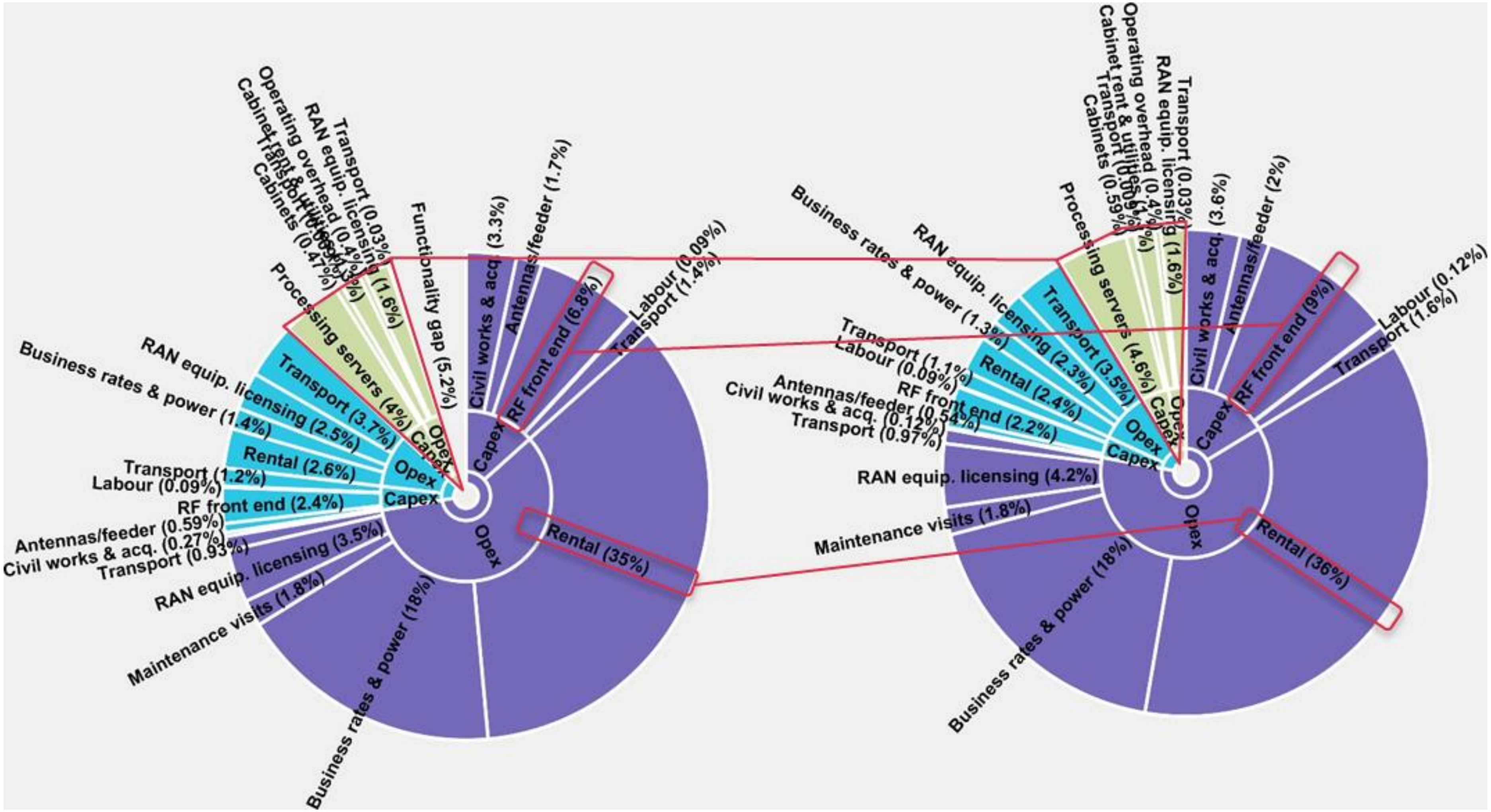



**Figure 3-21: Cost components affected by introducing the smart meter at sub-1GHz slice. eMBB only network cost components (left) and eMBB plus smart meter services at 800MHz (right)**

The premium attributed to supporting the smart meter slice is on increased macrocell CAPEX and OPEX, contributing 6% increase over the eMBB network, and on additional CAPEX and OPEX at the edge could, contributing 1% increase over the eMBB network. Savings from the shrinking the small cell layer, which are discussed below, bring the premium to 5.2%. Note that even though smart-meter traffic-volume is trivial when compared to that of eMBB (0.0070%), the challenging coverage requirements associated with reaching smart meter devices in difficult indoor locations and our assumption that these will be low cost devices supporting a single sub-1GHz frequency band means that there is a disproportionate cost increase from adding the smart meter services to the eMBB network. In short, support of indoor smart meter traffic increases the network TCO by 5.2% over the 11-year period due to the high indoor coverage requirement.

Looking first and the differences in macrocell costs in Figure 3-21. Smart meter traffic is envisioned to be accommodated on the sub-1GHz layer and exclusively from macrocells in the scenario shown. The comparison graph in Figure 3-21 shows that, there is additional CAPEX on the macrocell layer and there is also an increase in OPEX. This indicates that, support of the additional slice requires more macrocell infrastructure. This shows a repurposing of the network to accommodate the sub-1GHz band on more macrocell sites to accommodate this new service.

Since data processing of the macrocell layer occurs at the edge cloud a similar smart-meter service-premium incurs at the edge cloud. The premium is mainly attributed to increased CAPEX for processing servers because of their relatively short end-of-life cycle.

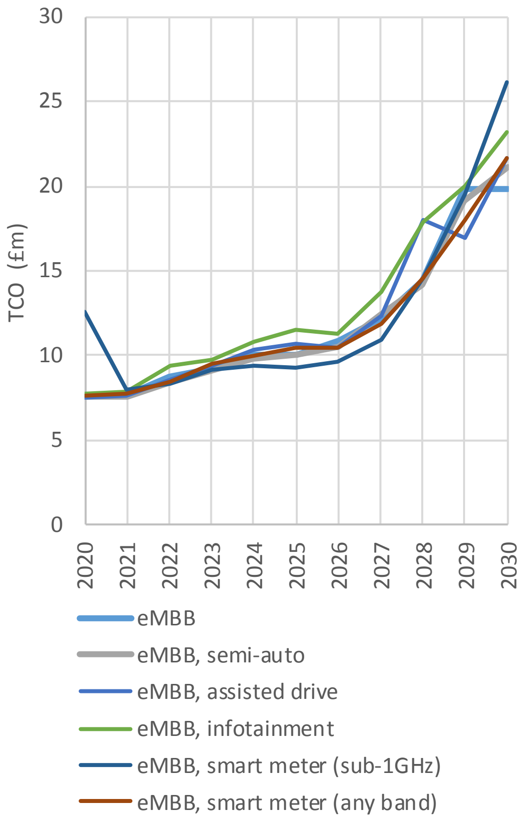
Looking next at small cells, the smart meter traffic is accommodated exclusively by macrocells, and the smart-meter low-datarate traffic-volume is trivial when compared to eMBB 4K video streaming. eMBB benefits from the additional macrocell infrastructure built to support small cell traffic and thus investment in the small cell layer is slightly reduced. There is 1% reduction in both small cell CAPEX and OPEX over the eMBB network.

Note in the network dimensioning applied in the cost model, higher frequency bands with wider bandwidths are preferred for serving high throughput eMBB services and so when smart meter services are introduced in 2020 there is limited existing support for the sub-1GHz band in our scenario. Investment to repurpose the network for smart meter services and to build this sub-1GHz infrastructure may be lower if:

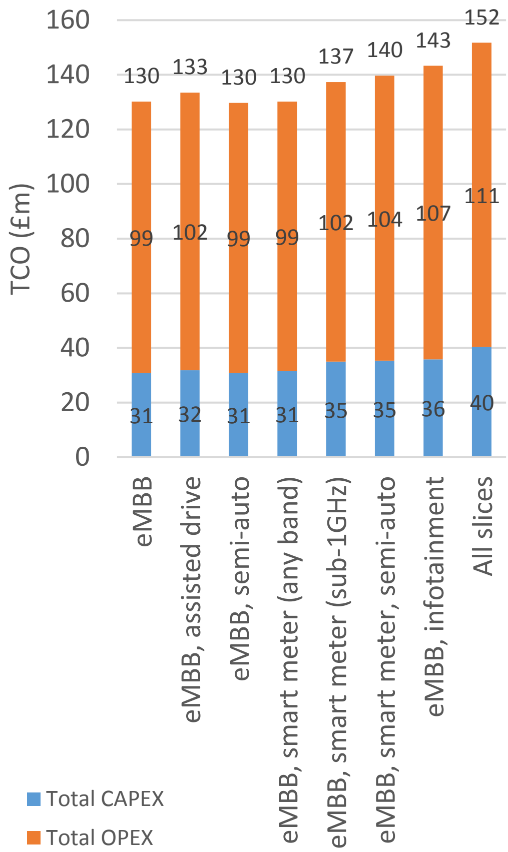
the existing eMBB targeted network prior to 2020 already includes some deployment of sub-1GHz spectrum on sites (which we believe would be the case in many of today's networks)
multi-tenancy in 5G NORMA is used to share site portfolios amongst multiple networks and provide virtual network densification to improve coverage confidence for these more challenging services as proposed in D3.3.

For the different cases of introducing new services to the network considered the TCO is shown in absolute numbers in Figure 3-22. The TCO percentage increase and the traffic demand increase with respect to the eMBB case are also shown in Table 3-12 and Table 3-13, respectively. Note for smart meter services we show two scenarios to indicate the two extremes of additional costs that might be incurred for adding this service to an existing eMBB network – one case assuming single band sub-1GHz smart meter devices (as discussed earlier) and one where any band can be used for smart meter devices (as a proxy to the reduction in repurposing costs that might be achieved in practice as per the points above).

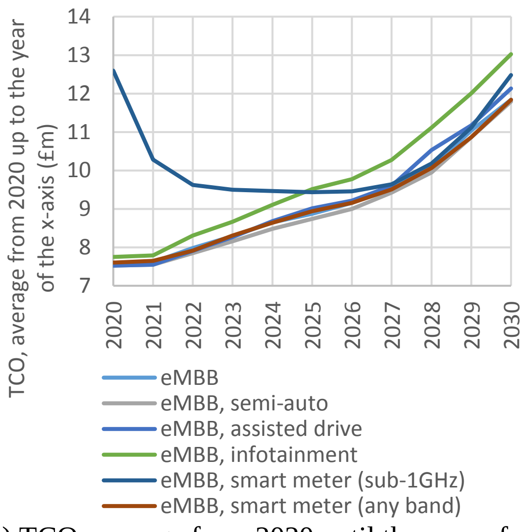
To comply with the requirements of each network slice the infrastructure needs to be repurposed accordingly. It can be seen that the smart meter slice has a compelling deep indoor coverage requirement and thus the network needs initial sub-1GHz carrier densification which raises the TCO early in the study period. However, in the case that smart meter services could be delivered on any frequency band the network does not need to densify the sub-1GHz layer and these additional costs disappear. This is also helped by the small volume of smart meter traffic which is temporally decorrelated with eMBB traffic. In contrast the infotainment slice has a traffic volume obligation that is in the same order of magnitude as eMBB and thus the network needs additional expenditure on resources for capacity throughout the study period.




(a) Annual TCO




(b) TCO, sum over the study period 2020-30




(c) TCO, average from 2020 until the year of the x-axis

**Figure 3-22: TCO with multiple slices**

**Table 3-12: CAPEX, OPEX and TCO percentage increase with respect to eMBB**

| | CAPEX | OPEX | TCO |
|---|---|---|---|
| eMBB/Smart meters (sub-1GHz only) | +13.9% | +2.8% | +5.2% |
| eMBB/Smart meters (any band) | +2.5% | -0.8% | ~0% |
| eMBB/Semi-automated driving | ~0% | ~0% | ~0% |
| eMBB/Assisted driving | +3.5% | +2.2% | +2.5% |
| eMBB/Infotainment | +16.8% | +7.9% | +10.0% |

**Table 3-13: Total traffic demand increase with respect to eMBB across the period 2020 to 2030**

| Smart meters | Semi-automated driving | Assisted driving | Infotainment |
|---|---|---|---|
| +~0% | +1.4% | +1.9% | +48% |

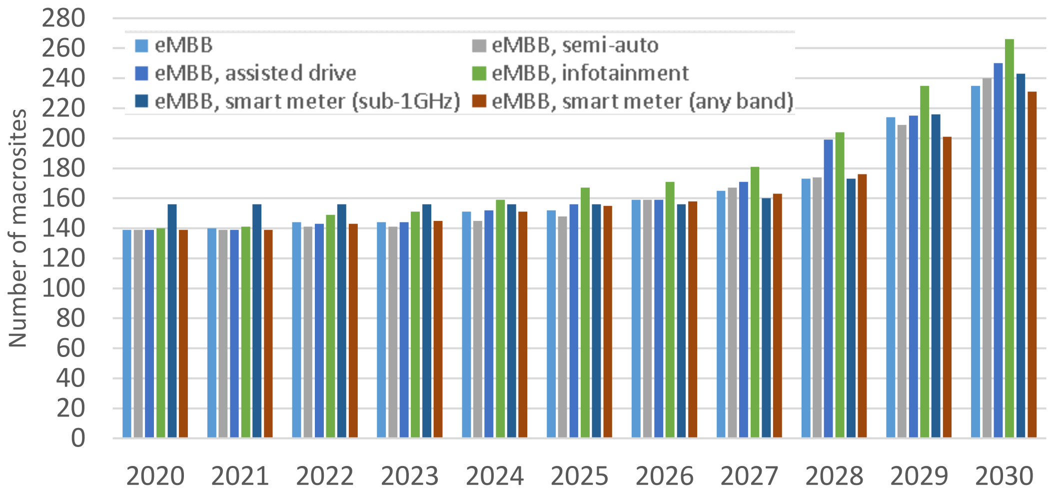
Assisted driving as an additional slice in parallel to eMBB also shows a disproportionate increase in the cost when compared to the demand, where a 1.9% increase of demand leads to a 2.5% increase in TCO. On the other hand, semi-automated driving's 1.4% increase of demand leads to about 0% increase TCO. It is noted that both services do not need network densification in 2020 because the range of the high availability of macrocells in the study area, see Table 2-16. This is even the case for semi-automated driving with a high coverage confidence target of 99.9% compared with 95% for the other services.

Note the traffic increment over existing eMBB traffic levels is lower for semi-automated driving services compared with assisted driving services because a faster uptake of assisted driving services is assumed (see Section 4.2.1.1). Therefore, even though both vehicular services are a small increment on top of eMBB traffic volume, the increase caused by assisted driving causes the network to exceed its existing capacity in 2028 and require macrocell densification slightly earlier than in the eMBB only scenario. This is why assisted driving services incur a higher cost penalty than semi-automated driving services despite the higher coverage confidence requirements of semi-automated driving services.

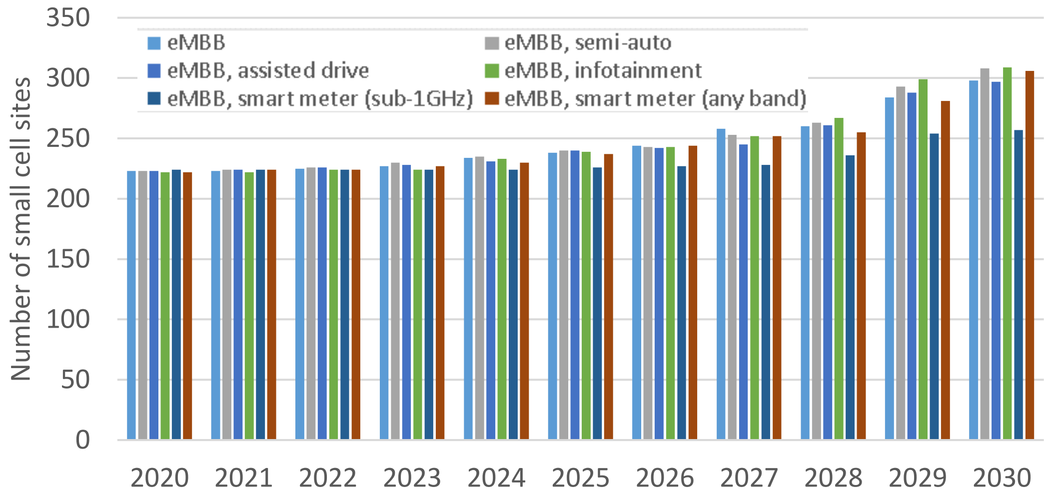
The infotainment result displays an economy of scale, i.e. 48% extra traffic causes a 10.0% increase in network expenditure because equipment is being utilised better. Infotainment incurs a higher cost to the network due to the increased investment to cope with the higher traffic, but with a better proportion between traffic and cost, exhibiting an economy of scale.

Note though that in our central London scenario the existing site density is relatively high compared to other environments. The effect of increased network costs to accommodate more challenging services in terms of coverage and reliability will be more apparent in other environments with less dense existing site deployments. Therefore, the potential benefits of virtual network densification achieved from sharing antenna site portfolios under a multi-tenant 5G NORMA network could be increased in these areas compared with the central London scenario examined here.

Figure 3-23 shows the number of macrocell and small cell antenna sites. Introducing additional slices require a greater number of macrocell sites by 2030. In the case of indoor mMTC services investment is required upfront in 2020 to meet service requirements, which results in a higher spend over the 10-year period. Due to the increased number of macrocell sites to serve deep indoors, incidentally more eMBB traffic is served by the macrocell layer and the small cell layer is reduced. eMBB/infotainment requires an increased number of macrocell and small cell sites, throughout the 2020-2030 period.




(a) Number of macrocell antenna sites over time




(b) Number of small cell sites over time

**Figure 3-23: Number of antenna sites**

#### 3.3.1.2 CAPEX results

Figure 3-24 shows the CAPEX values for the six cases studied. The macrocell antenna site CAPEX dominates the CAPEX per year in all cases. There is also a considerable amount of CAPEX for edge cloud sites in later years. This is due to increasing processing requirements over time to support higher capacity in the network which needs to be accommodated at the edge cloud sites and also due to the short life expectation of commercial-off-the-shelf (COTS) edge cloud server equipment (4 years as opposed to 10 years for telco grade hardware as used for baseband units at macrocell antenna sites in the D-RAN case). The small cell CAPEX is almost the same for every case at each year; they are indifferent to the additional slices (since these are primarily served by the macrocells).

When the smart meter is served on the sub-1GHz layer there is a spike of CAPEX on the first year of service, because of the network's repurposing, which is repeated ten years later due to the refresh cycle. Note that heavy spending in 2020 builds an excess of capacity for eMBB which is expressed by reduced CAPEX in the following 8 years.

When the non-eMBB service can be accommodated in any band the network has enough density and does not need densification.

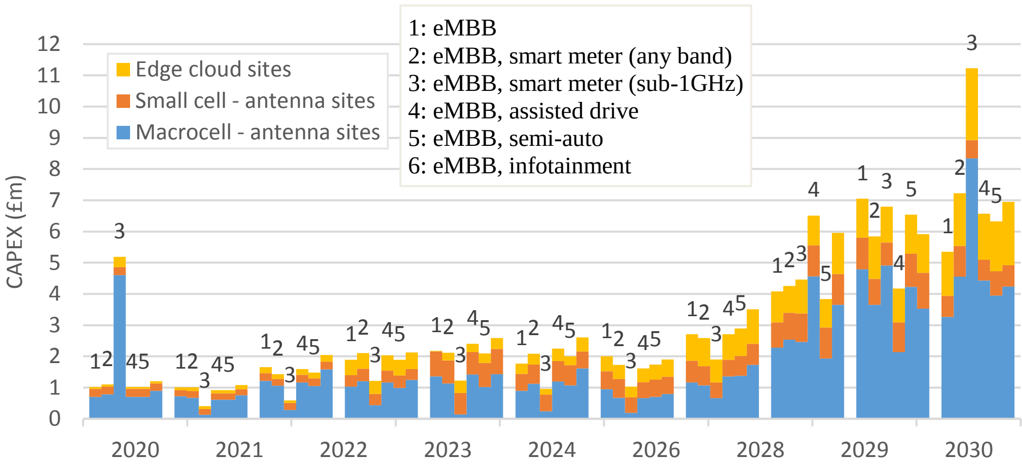



**Figure 3-24: CAPEX results for multi-service scenarios considered**

#### 3.3.1.3 OPEX results

Figure 3-25 shows the OPEX results for the six cases studied. The macrocell antenna site OPEX dominates the OPEX per year in all cases. The edge cloud site OPEX grows more significant over time as the capacity to be processed at the edge cloud sites grows. Overall, OPEX expenditure shows a slight increase due to the additional services.

Following similar trend as CAPEX when the smart meter is served on the sub-1GHz layer there is a spike of associated increase in OPEX which is not observed when all bands are utilised.

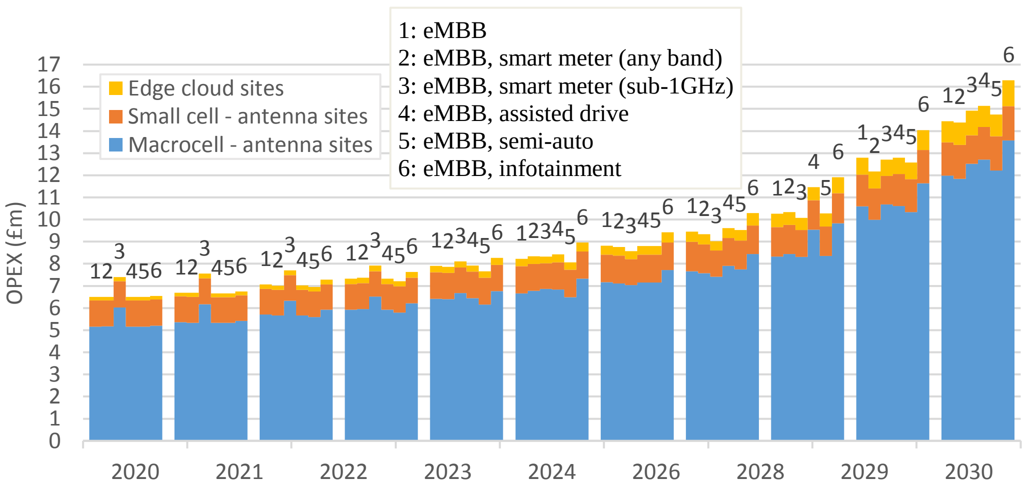



**Figure 3-25: OPEX results for multi-service scenarios considered**

### 3.3.2 Conclusions

To assess the cost of multi-slice support we simulated a network with 1 slice (eMBB) from 2020 to 2030, and different multi-service networks supporting network slice combinations such as eMBB and smart meters and eMBB and different V2I services. All networks shared the same initial 2020 deployment and were then allowed to evolve per year in the most economical fashion based on a present value TCO optimiser. We compared TCO, CAPEX and OPEX between the networks supporting different service combinations.

Across the scenarios examined, the cost of the network was mainly eMBB-driven, made up of eMBB and in one case also infotainment. Other non-eMBB services examined (smart meters, semi-automated driving, and assisted driving) are each less than 2% and combined less than 4% of the eMBB traffic volume.

There is a disproportionate increase in the cost when compared to the demand of some non eMBB services. For example, there is a 0.0070% increase in overall network traffic when the smart meter traffic is introduced, but a 5.2% increase in the network cost, due to the early initial investment for building the sub-1GHz capability into the network to support deep indoor penetration.

Infotainment incurs a high cost increment to the network due to the increased investment to cope with the higher traffic, but with a better proportion between traffic and cost (48% increase in traffic, but 10% increase in cost), exhibiting an economy of scale. Semi-automated driving with a high coverage confidence target of 99.9% but low traffic volume was accommodated on the eMBB network with near zero increase in costs due to the already high density of sites in the study area. Assisted driving services with a higher traffic increment over eMBB services of 1.9% caused network densification in hotspot areas to occur slightly earlier than in the eMBB only scenario resulting in a 2.5% increase in costs.

# 4 Revenue opportunities with 5G NORMA and the evolving business case

This chapter looks at the business case for network operators to deploy 5G networks based on the 5G NORMA architecture. It combines the results of our cost modelling with revenue forecasts for a set of services that we believe are likely to be among the most prominent services for 5G in the future:

- eMBB – as an anchor service;
- V2X;
- Smart city (intelligent transport systems, smart energy metering/grids and smart water);
- Logistics.

The analysis is for the Central London area. We believe the business case is likely to be the most positive of any area in the UK for a number of reasons. The revenues per square km is significant because the area is densely populated. Levels of economic activity in this area are also high which should fuel the demand for a range of 5G services. On the cost side, there is good fibre availability at competitive prices. As a result, this area is also likely to be the best candidate location type for the start of migration to 5G.

The traffic and revenue forecasts which underlie our business case analysis are the result of many separate pieces of research. We began with a thorough review of potential 5G use cases in [5GN-D21]. Subsequently, [5GN-D22] identified key market segments, vertical users and initial business models and [5GN-D33] assessed functional requirements that the 5G NORMA architecture should satisfy.

The business cases consider the incremental costs of deploying the 5G NORMA network and the direct revenues from selling the selected 5G services. Using the terminology of the new stakeholder roles expected to emerge in 5G (shown in Section 1.4) we look at:

- The direct revenues and costs from MSPs[9] (Mobile Service Providers) providing eMBB services to end-users in the first instance (Evaluation Case 1);
- We then broaden the analysis to consider tenants as eMBB retailers (they could also be end-users in their own right and self-provide eMBB) and look at the implications for the business case of the 5G NORMA multi-tenancy innovation (Evaluation Case 2);
- Finally, we consider tenants as providers of differentiated services (V2X, smart city, logistics) and examine the impact of providing these services over a single, multi-service, network – also a 5G NORMA innovation (Evaluation Case 3).

In addition, we expect that the wider socio-economic benefits from 5G services could be substantial and that significant value could be created as new, disruptive business models emerge and drive innovation in applications and content services. The nature of the relationship between MSP and tenant can vary and would be encapsulated in the "offer type" from the MSP. [5GN-D32] described three offer types which give the tenant varying degrees of control over the network slice configuration. There may be a link between the degree of control that the tenant has over their own network slice and the level of innovation in end-user applications. For example, for applications requiring high security it may be essential for the tenant to physically own and locate some of the network infrastructure and processing of some higher layers on their own site. These issues are considered in more detail in Chapter 5 and Chapter 6.

[9] The difference between an MSP and an MNO is that the former leases all needed physical and virtual resources from one or multiple InPs to deploy the end-to-end mobile network whereas the MNO owns and operates the physical and virtual network functions.

There is a considerable level of uncertainty in making revenue forecasts. However, our analysis is grounded in a substantial amount of evidence including published research on 5G developments, plans and strategies across the relevant verticals and publicly available market research and forecasts. Due to the uncertainty, we have developed a range of forecasts covering *low, middle and high* estimates for 5G revenues.

Another difficulty is the limited evidence base for predicting end-user responses to issues such as changes in service functionality, and the emergence of completely new services. However, past consumer behaviour in the face of innovation is relatively consistent and we have relied on the established body of work in this area in telecommunications.

## 4.1 eMBB services

First, we present a summary of our estimates of incremental 5G eMBB revenues including a brief description of the services and our methodology. We then combine the revenues with the cost modelling results to present business cases for each of the three Evaluation Cases described above.

### 4.1.1 eMBB revenue forecasts

eMBB is expected to provide substantially higher throughput than today at lower latency (though it will not require the latency necessary for uMTC applications) and in many different environments e.g.: in the home; office; outdoor environments and events and in vehicles. The key applications driving demand are assumed to be video-based (4k video streaming assumed as sufficient resolution) as well as standard voice, messaging and data use. Augmented and Virtual Reality (AR/VR) are frequently identified as extreme broadband applications requiring 5G for a consistent user experience. It is assumed that VR will take place largely indoors and would be carried over dedicated indoor networks. AR services are more amenable to outdoor use, so we assume that the 5G NORMA architecture modelled will support this.

We identified five market segments for eMBB and identified the number of potential users, eMBB take-up, and average revenue per subscriber in each:

- Pre-pay users;
- Post-pay users:
  - Early adopters;
  - Mainstream;
  - Laggards;
- Business users (individuals whose organisations pay for the mobile subscription and usage).

Some operators are already beginning to market services delivered over LTE-A Pro as 5G services. However, with 5G we mean services delivered over true 5G networks.

#### 4.1.1.1 Customer segments

Pre-pay and post-pay users are modelled because these segments are quite distinctive in terms of willingness to pay. The proportion of pre-pay subscribers assumed is 40% [Ofc16b]. For the post-pay market segments, we follow the classic literature on technology diffusion, e.g. [Rog62], and noted in the table below. Early adopters are likely to be heavy and intensive users relatively insensitive to price. Mainstream users are assumed to be close to the average user and laggards as representative of light users, but not as price sensitive as pre-pay users.

**Table 4-1: Proportion of subscribers by market segment**

| Market segment | Proportion of total market |
|---|---|
| **Pre-pay** | 34.1% (39.5% of consumer subscriptions) |
| **Early adopter** | 8.4% (16% of post-pay) |
| **Mainstream** | 35.6% (68% of post-pay) |
| **Laggard** | 8.4% (16% of post-pay) |
| **Business** | 13.6% |

#### 4.1.1.2 Service take-up by segment

We model service take-up for each of the four market segments described in the previous section. We would expect take-up to be faster in areas with above average income, such as Central London, than for the UK as a whole. However, in order to simplify the analysis, we assume that service take-up is the same for Central London as for the UK as a whole. The take-up projections and the resulting total number of subscribers in the Central London area are shown in the two tables Table 4-2 and Table 4-3 below.

**Table 4-2: eMBB service take-up by market segment**

| | 2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 | 2029 | 2030 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Early Adopters** | 11% | 21% | 29% | 36% | 42% | 49% | 57% | 66% | 77% | 90% | 96% |
| **Mainstream** | 0.5% | 3% | 11% | 21% | 29% | 36% | 42% | 49% | 57% | 66% | 77% |
| **Laggards** | 0% | 0% | 1% | 3% | 11% | 21% | 29% | 36% | 42% | 49% | 57% |
| **Pre-pay** | 0% | 0% | 1% | 3% | 11% | 21% | 29% | 36% | 42% | 49% | 57% |
| **Business** | 6% | 12% | 20% | 28% | 35% | 42% | 50% | 58% | 67% | 78% | 87% |

**Table 4-3: Central London eMBB subscribers by market segment**

| | 2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 | 2029 | 2030 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Early Adopters** | 4,966 | 9,554 | 13,068 | 16,406 | 19,556 | 22,981 | 26,838 | 31,336 | 36,603 | 42,736 | 45,913 |
| **Mainstream** | 959 | 5,800 | 21,437 | 41,245 | 56,398 | 70,760 | 84,047 | 98,417 | 114,961 | 134,221 | 156,778 |
| **Laggards** | 0 | 0 | 229 | 1,386 | 5,122 | 9,849 | 13,419 | 16,777 | 19,931 | 23,339 | 27,261 |
| **Pre-pay** | 0 | 0 | 936 | 5,658 | 20,904 | 40,197 | 54,769 | 68,474 | 81,347 | 95,254 | 111,262 |
| **Business** | 4,208 | 8,849 | 14,679 | 21,161 | 26,604 | 32,118 | 37,778 | 44,163 | 51,587 | 60,230 | 67,106 |

5G post-pay service take-up is modelled on the historical and predicted penetration of 4G (as a percentage of all subscribers). This data is taken from [Gsm15] and is fitted to the mainstream market segment. We assume the early adopter market segment is 2 years in advance of the mainstream and that the laggard and pre-pay market segments lag the mainstream by 2 years. Business take-up is modelled as an average of early adopters and the mainstream.

We have used the residential population of Central London to forecast eMBB subscribers and revenues. This is predicted to rise from 414,300 to 438,900 between 2010 and 2030 according to [Gla17]. We chose the more simplistic approach to assessing the relevant population to calculate revenues. However, the population of the area varies over the course of the day. The daytime population will be swelled by non-residents who work or travel to Central London. Some Central London residents will work outside the area, however this effect is likely to be smaller than the first. A more sophisticated approach would have taken into account these changes in population. However we would have had to choose a basis on which to allocate the revenues of the different groups of subscribers. Given that most subscribers pay a fixed monthly subscription rather than per call or data session, there is no unique way of doing this.

#### 4.1.1.3 Average Revenue per Subscriber (ARPS) by market segment

There is uncertainty whether eMBB will lead to an uplift in mobile broadband revenues, especially since overall ARPS for mobile services has remained relatively constant despite the introduction of 4G services in recent years[10]. However, [Mob17] reports evidence that 75% of businesses are prepared to pay more (from 10% to at least 30%) for faster speeds compared to today's mobile services. We also consider that innovations such as AR could make a palpable difference to the value that consumers get from eMBB. We consider that eMBB traffic will be related to the extent to which higher value applications such as AR are used and this will feed through into the ARPS. The magnitude of this effect is uncertain and we capture this by making low, middle and high estimates for ARPS.

We assume that pre-pay ARPS stays at the same level across the three scenarios. For post-pay services we make the following assumptions. In the low case, we assume that ARPS will be the same on average across all subscribers as for 4G today. The middle case is the average of the low and high cases. In the high case, we make a number of specific assumptions:

- Early adopters will derive a similar benefit to a current superfast fixed broadband connection (including line rental) and will be willing to pay a similar price.
- Mainstream subscribers pay a significant premium for better performance (leading to an ARPS similar to that observed 5 years ago in the UK for 3G post-pay subscribers).
- Laggards will pay a moderate premium for better performance compared to the 4G ARPS we infer for laggards – 20%.
- The variation between the low and high scenario for business ARPS is assumed to be the same as for early adopters. The low scenario estimate is based on information on average mobile revenues per business subscriber in [Ofc16b] for 4G services.

**Table 4-4: Monthly ARPS by market segment**

| | 5G Low | 5G Middle | 5G High |
|---|---|---|---|
| **Pre-pay** | £5 | £5 | £5 |
| **Early adopter** | £30 | £35 | £40 |
| **Mainstream** | £20 | £22 | £24 |
| **Laggard** | £10 | £11 | £12 |
| **Business** | £24 | £28 | £32 |

#### 4.1.1.4 eMBB revenue forecast

We present below, in Table 4-5 and Table 4-6, the results of our projection of eMBB revenues for our Central London Area and the UK as a whole to give some broader context to the figures. The tables below show the increase in revenue for eMBB delivered over a true 5G network.

[10] Although the GSMA suggests that increasing LTE penetration may be beginning to cause an increase in mobile revenues, https://www.gsma.com/newsroom/press-release/gsma-study-5g-account-third-europes-mobile-market-2025/

**Table 4-5: eMBB revenue forecast, middle scenario, £ million, UK**

| | 2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 | 2029 | 2030 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Early Adopters** | 339 | 651 | 889 | 1,115 | 1,327 | 1,557 | 1,821 | 2,130 | 2,492 | 2,915 | 3,134 |
| **Mainstream** | 41 | 249 | 917 | 1,762 | 2,406 | 3,013 | 3,585 | 4,206 | 4,920 | 5,755 | 6,727 |
| **Laggards** | 0 | 0 | 5 | 30 | 109 | 210 | 286 | 358 | 426 | 500 | 585 |
| **Pre-pay** | 0 | 0 | 9 | 55 | 203 | 389 | 531 | 665 | 791 | 928 | 1,085 |
| **Business** | 230 | 483 | 799 | 1,150 | 1,444 | 1,741 | 2,051 | 2,402 | 2,810 | 3,287 | 3,665 |
| **Total Middle** | 610 | 1,382 | 2,620 | 4,111 | 5,489 | 6,909 | 8,274 | 9,761 | 11,439 | 13,385 | 15,195 |
| | | | | | | | | | | | |
| **Total Low** | 525 | 1,198 | 2,295 | 3,625 | 4,864 | 6,145 | 7,369 | 8,699 | 10,196 | 11,931 | 13,559 |
| **Total High** | 695 | 1,567 | 2,945 | 4,597 | 6,113 | 7,673 | 9,179 | 10,824 | 12,682 | 14,840 | 16,831 |

**Table 4-6: eMBB revenue forecast, middle scenario, £ million, Central London Area**

| | 2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 | 2029 | 2030 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Early Adopters** | 2.1 | 4.0 | 5.5 | 6.9 | 8.2 | 9.7 | 11.3 | 13.2 | 15.4 | 17.9 | 19.3 |
| **Mainstream** | 0.3 | 1.5 | 5.7 | 10.9 | 14.9 | 18.7 | 22.2 | 26.0 | 30.3 | 35.4 | 41.4 |
| **Laggards** | 0.0 | 0.0 | 0.0 | 0.2 | 0.7 | 1.3 | 1.8 | 2.2 | 2.6 | 3.1 | 3.6 |
| **Pre-pay** | 0.0 | 0.0 | 0.1 | 0.3 | 1.3 | 2.4 | 3.3 | 4.1 | 4.9 | 5.7 | 6.7 |
| **Business** | 1.4 | 3.0 | 4.9 | 7.1 | 8.9 | 10.8 | 12.7 | 14.8 | 17.3 | 20.2 | 22.5 |
| **Total Middle** | 3.8 | 8.5 | 16.2 | 25.4 | 34.0 | 42.8 | 51.2 | 60.3 | 70.6 | 82.4 | 93.5 |
| | | | | | | | | | | | |
| **Low** | 3.2 | 7.4 | 14.2 | 22.4 | 30.1 | 38.1 | 45.6 | 53.7 | 62.9 | 73.5 | 83.4 |
| **High** | 4.3 | 9.7 | 18.2 | 28.4 | 37.8 | 47.6 | 56.8 | 66.9 | 78.2 | 91.4 | 103.6 |

We model take-up of eMBB services and the infrastructure to support them over a pre-existing network. So in addition to eMBB traffic, the network is also carrying traffic from legacy mobile broadband (MBB) subscribers. Table 4-7 below shows eMBB and legacy MBB revenues together. For comparison, UK mobile retail revenues in 2016 were £15.3 billion, according to Ofcom [Ofc17]. Hence, our forecast for 2020 appears to be in the right ballpark.

**Table 4-7: eMBB and legacy MBB revenues, middle scenario, £ billion, UK and Central London**

| | 2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 | 2029 | 2030 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **eMBB UK** | 0.61 | 1.38 | 2.62 | 4.11 | 5.49 | 6.91 | 8.27 | 9.76 | 11.44 | 13.39 | 15.20 |
| **Legacy MBB UK** | 14.78 | 14.48 | 13.85 | 12.96 | 11.87 | 10.65 | 9.59 | 8.49 | 7.31 | 5.95 | 4.56 |
| **Total UK** | **15.39** | **15.86** | **16.46** | **17.07** | **17.36** | **17.56** | **17.87** | **18.26** | **18.75** | **19.34** | **19.75** |
| **eMBB Central London** | 0.00 | 0.01 | 0.02 | 0.03 | 0.03 | 0.04 | 0.05 | 0.06 | 0.07 | 0.08 | 0.09 |
| **Legacy MBB Central London** | 0.09 | 0.09 | 0.09 | 0.08 | 0.07 | 0.07 | 0.06 | 0.05 | 0.05 | 0.04 | 0.03 |
| **Total Central London** | **0.09** | **0.10** | **0.10** | **0.11** | **0.11** | **0.11** | **0.11** | **0.11** | **0.12** | **0.12** | **0.12** |

### 4.1.2 Business case for eMBB scenarios

The next sections combine our revenue forecasts with our cost modelling results to draw out the financial implications of our work. These findings are only tentative at this stage for a number of reasons.

Firstly, we only modelled the network costs of the 5G NORMA based network. The cost model does not include general administrative costs such as the cost of office space and equipment. Nor does it include sales and marketing expenses such as billing. So, we have taken a high level approach to get at least an indication of these costs so that we can make a better comparison with the revenues.

- Based on information from industry experts, we estimate that core network costs will add an extra 10% to the access network costs we modelled;
- There was little public domain information on administrative costs as a proportion of total costs (cost of sales in accounting terms) for the UK since none of the operators is separately listed. Hence, we relied on figures for the Vodafone Group, of which the UK business is a substantial component. This gave administrative and retail costs as 30% of the total cost of sales [Vod17].

In addition, we have not taken into account the cost for the MANO framework. This would require drastic changes in terms of infrastructure (and the business model) and the costs of this are uncertain at the moment. Nonetheless, we believe that the cost figures we have produced are a reasonable first estimate.

Secondly, the 5G NORMA network supports both 5G eMBB traffic and legacy mobile broadband traffic. 5G eMBB traffic grows as subscribers switch to this service over time from their previous mobile subscriptions. Legacy mobile broadband is the traffic from the remaining mobile subscribers who have not yet switched over to 5G eMBB. As a result, we need to add in the revenues from these legacy MBB subscribers so that the revenues are consistent with the costs.

Finally, we look at the evolution of costs and revenues (undiscounted) over time and calculate an indicative return on investment (ROI) also undiscounted. The ROI is calculated as:

$$\text{ROI} = (\text{Total revenues} - \text{Total Costs})_{2020\text{-}2030} \text{ divided by Total Costs}_{2020\text{-}2030}$$

We also calculate discounted cash flows. The discounted cash flow expresses the value of future cash flows in terms of today's money. It is calculated as the difference between revenues and the sum of operating and capital expenses each year discounted by the cost of capital of a typical mobile operator. The sum of the discounted cash flows over a period of time is equal to the Net Present Value (NPV) a commonly used measure of economic and financial value. We used a discount rate of 7% taken from [Ofc15].

#### 4.1.2.1 Business case for eMBB: C-RAN compared to D-RAN

**Baseline Case**

Table 4-8, Table 4-9, and Table 4-10 below show the evolution of the relevant costs and revenues over time for Evaluation Case 1 and our indicative ROI. The first table presents the network costs, our high level estimate of the total costs (including admin and retail) and the eMBB plus legacy MBB revenues. The second table shows the total cost and the indicative ROI. The results are for a single network operator with an 18% share of the market and a pre-existing network prior to the start of the model period which starts to provide eMBB services in the Central London area from 2020 onwards in line with the typical market share of MNOs in the UK today.

**Table 4-8: Evaluation Case 1: cost and revenue results combined, middle scenario, £ million, Central London**

| | 2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 | 2029 | 2030 | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **D-RAN access cost** | 6.61 | 8.43 | 9.15 | 9.51 | 10.40 | 10.09 | 10.48 | 12.27 | 14.08 | 16.65 | 18.62 | 126.3 |
| **C-RAN access cost** | 6.24 | 8.03 | 9.09 | 9.62 | 10.42 | 10.35 | 10.62 | 13.41 | 14.70 | 16.38 | 19.94 | 128.8 |
| **D-RAN full cost** | **10.41** | **13.28** | **14.42** | **14.98** | **16.38** | **15.90** | **16.51** | **19.32** | **22.17** | **26.22** | **29.33** | **198.9** |
| **C-RAN full cost** | **9.82** | **12.64** | **14.32** | **15.15** | **16.41** | **16.29** | **16.73** | **21.12** | **23.16** | **25.80** | **31.40** | **202.9** |
| **eMBB revenues** | 0.68 | 1.53 | 2.91 | 4.57 | 6.11 | 7.71 | 9.22 | 10.85 | 12.70 | 14.83 | 16.83 | 88.0 |
| **Legacy MBB revenues** | 16.36 | 16.06 | 15.38 | 14.42 | 13.22 | 11.89 | 10.69 | 9.45 | 8.12 | 6.60 | 5.05 | 127.2 |
| **Total revenue** | **17.04** | **17.59** | **18.29** | **18.99** | **19.34** | **19.60** | **19.91** | **20.30** | **20.82** | **21.43** | **21.88** | **215.2** |

**Table 4-9: Evaluation Case 1: cumulative discounted cash flow, middle scenario, £ million, Central London**

| | 2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 | 2029 | 2030 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **D-RAN** | 6.63 | 10.65 | 14.04 | 17.31 | 19.57 | 22.21 | 24.48 | 25.09 | 24.30 | 21.70 | 17.91 |
| **C-RAN** | 7.21 | 11.83 | 15.30 | 18.44 | 20.67 | 23.02 | 25.14 | 24.63 | 23.27 | 20.90 | 16.06 |

**Table 4-10: Evaluation Case 1: summary financial measures, middle scenario, £ million, Central London**

| | NPV £ million | Indicative ROI |
|---|---|---|
| **D-RAN** | 17.91 | 8% |
| **C-RAN** | 16.06 | 6% |

Although over the 10-year period, our indicative figures show there is a positive business case (D-RAN and C-RAN are very similar), the trend reveals some potential concerns. Total costs overtake total revenues in the final years of the model period. It is not clear how much this is due to a real underlying trend and how much it is due to the lumpiness of investment leading to substantial unused capacity. However, there is a risk that it becomes challenging for eMBB revenues on their own to cover the costs of meeting the traffic growth and performance requirements of eMBB. The moderate increase in eMBB subscriber revenues compared to today appears unlikely to be sufficient, noting that some commentators believe that revenues may not even be any higher than today.

**Sensitivity analysis: variations in traffic costs and revenues**

We have carried out a number of sensitivities to examine the robustness of our results. Table 4-11, Table 4-12, and Table 4-13 below show the results for two set of sensitivities: we combine the low revenue scenario (described earlier in this chapter) with the low traffic scenario costs and we combine the high revenue scenario with the high traffic scenario costs.

***Low revenues, low traffic sensitivity***

**Table 4-11: Evaluation Case 1 sensitivity: cost and revenue results combined, low revenues, low traffic, £ million, Central London**

| | 2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 | 2029 | 2030 | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **D-RAN access cost** | 6.61 | 7.22 | 8.55 | 9.11 | 9.43 | 8.89 | 8.96 | 9.46 | 10.36 | 10.21 | 10.47 | 99.3 |
| **C-RAN access cost** | 6.21 | 6.85 | 7.97 | 8.58 | 8.81 | 8.72 | 8.62 | 9.63 | 10.54 | 10.54 | 10.43 | 96.9 |
| **D-RAN full cost** | **10.41** | **11.37** | **13.47** | **14.36** | **14.85** | **14.00** | **14.12** | **14.91** | **16.31** | **16.08** | **16.50** | **156.4** |
| **C-RAN full cost** | **9.77** | **10.78** | **12.56** | **13.52** | **13.88** | **13.73** | **13.58** | **15.17** | **16.61** | **16.60** | **16.43** | **152.6** |
| **eMBB revenues** | 0.58 | 1.33 | 2.55 | 4.03 | 5.42 | 6.86 | 8.21 | 9.67 | 11.32 | 13.22 | 15.02 | 78.2 |
| **Legacy MBB revenues** | 16.36 | 16.06 | 15.38 | 14.42 | 13.22 | 11.89 | 10.69 | 9.45 | 8.12 | 6.60 | 5.05 | 127.2 |
| **Total revenue** | **16.94** | **17.38** | **17.93** | **18.45** | **18.64** | **18.74** | **18.90** | **19.12** | **19.44** | **19.82** | **20.06** | **205.4** |

**Table 4-12: Evaluation Case 1 sensitivity: cumulative discounted cash flow, low revenues, low traffic, £ million, Central London**

| | 2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 | 2029 | 2030 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **D-RAN** | 6.54 | 12.16 | 16.05 | 19.39 | 22.28 | 25.67 | 28.85 | 31.48 | 33.30 | 35.33 | 37.15 |
| **C-RAN** | 7.17 | 13.34 | 18.03 | 22.06 | 25.69 | 29.26 | 32.81 | 35.27 | 36.92 | 38.67 | 40.51 |

**Table 4-13: Evaluation Case 1 sensitivity: summary financial measures, low revenues, low traffic, £ million, Central London**

| | NPV £ million | Indicative ROI |
|---|---|---|
| **D-RAN** | 37.15 | 31% |
| **C-RAN** | 40.51 | 35% |

***High revenues, high traffic sensitivity***

**Table 4-14: Evaluation Case 1 sensitivity: cost and revenue results combined, high revenues, high traffic, £ million, Central London**

| | 2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 | 2029 | 2030 | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **D-RAN access cost** | 6.73 | 10.20 | 10.04 | 9.43 | 10.74 | 12.49 | 13.55 | 16.04 | 19.93 | 21.88 | 30.26 | 161.3 |
| **C-RAN access cost** | 6.42 | 9.02 | 9.34 | 10.10 | 10.58 | 13.31 | 13.22 | 17.78 | 21.14 | 24.98 | 26.15 | 162.0 |
| **D-RAN full cost** | **10.59** | **16.07** | **15.82** | **14.85** | **16.92** | **19.68** | **21.35** | **25.26** | **31.39** | **34.46** | **47.65** | **254.0** |
| **C-RAN full cost** | **10.11** | **14.21** | **14.71** | **15.91** | **16.67** | **20.96** | **20.82** | **28.01** | **33.30** | **39.35** | **41.19** | **255.2** |
| **eMBB revenues** | 0.77 | 1.74 | 3.27 | 5.12 | 6.81 | 8.56 | 10.23 | 12.04 | 14.08 | 16.45 | 18.64 | 97.7 |
| **Legacy MBB revenues** | 16.36 | 16.06 | 15.38 | 14.42 | 13.22 | 11.89 | 10.69 | 9.45 | 8.12 | 6.60 | 5.05 | 127.2 |
| **Total revenue** | **17.13** | **17.79** | **18.65** | **19.53** | **20.03** | **20.45** | **20.92** | **21.48** | **22.20** | **23.04** | **23.69** | **224.9** |

**Table 4-15: Evaluation Case 1 sensitivity: cumulative discounted cash flow, high revenues, high traffic, £ million, Central London**

| | 2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 | 2029 | 2030 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **D-RAN** | 6.54 | 8.15 | 10.62 | 14.44 | 16.81 | 17.37 | 17.08 | 14.72 | 9.38 | 3.17 | -9.01 |
| **C-RAN** | 7.02 | 10.36 | 13.81 | 16.77 | 19.33 | 18.97 | 19.03 | 14.97 | 8.51 | -0.36 | -9.26 |

**Table 4-16: Evaluation Case 1 sensitivity: summary financial measures, high revenues, high traffic, £ million, Central London**

| | NPV £ million | Indicative ROI |
|---|---|---|
| **D-RAN** | -9.01 | -11.5% |
| **C-RAN** | -9.26 | -11.9% |

Table 4-14, Table 4-15, and Table 4-16 above show that the high revenues, high traffic growth sensitivity is a more challenging business case than that for the baseline middle scenario. This is because the potential for revenue growth is strictly limited and is outstripped by the increase in traffic (and the cost of serving that traffic) due to the non-linear relationship between revenues and traffic.

In contrast, in the low revenues, low traffic growth scenario, the return on investment is higher than in the middle scenario because the difference in traffic, and therefore costs, is again much larger than the difference in revenues.

As highlighted in Section 2.3.3 already, in practice MNOs have some control over the traffic growth scenario that occurs as this will be linked to the data plans offered and in turn the competition in the market and commercial tariffs evolution. The results of this sensitivity analysis imply that, given the limited scope to increase eMBB revenues, it would be most commercially viable for MNOs focusing on an eMBB only strategy to limit growth in demand volumes and hence network costs where possible. This has implications for governments and regulators as it raises concerns that mobile networks, if left to market mechanisms, may not deliver sufficient capacity to support the full potential for growth in eMBB services and hence limit innovation and the benefits derived from these services.

**Sensitivity analysis: reduction in middle scenario revenues**

We present the results for two more sensitivities in the tables below. Here we look at the sensitivity of the results to a reduction in revenues in isolation. We apply an across the board cut in the middle scenario revenues of 15% and 30% while using the baseline cost results. We have not tested the impact of increasing middle scenario revenues because the business case for the middle scenario is already positive.

***Revenues reduced by 15% across the board***

**Table 4-17: Evaluation Case 1 sensitivity: cost and revenue results combined, middle scenario revenue minus 15%, £ million, Central London**

| | 2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 | 2029 | 2030 | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **D-RAN access cost** | 6.61 | 8.43 | 9.15 | 9.51 | 10.40 | 10.09 | 10.48 | 12.27 | 14.08 | 16.65 | 18.62 | 126.3 |
| **C-RAN access cost** | 6.24 | 8.03 | 9.09 | 9.62 | 10.42 | 10.35 | 10.62 | 13.41 | 14.70 | 16.38 | 19.94 | 128.8 |
| **D-RAN full cost** | **10.41** | **13.28** | **14.42** | **14.98** | **16.38** | **15.90** | **16.51** | **19.32** | **22.17** | **26.22** | **29.33** | **198.9** |
| **C-RAN full cost** | **9.82** | **12.64** | **14.32** | **15.15** | **16.41** | **16.29** | **16.73** | **21.12** | **23.16** | **25.80** | **31.40** | **202.9** |
| **eMBB revenues** | 0.57 | 1.30 | 2.47 | 3.89 | 5.20 | 6.55 | 7.84 | 9.23 | 10.80 | 12.61 | 14.30 | 74.8 |
| **Legacy MBB revenues** | 16.36 | 16.06 | 15.38 | 14.42 | 13.22 | 11.89 | 10.69 | 9.45 | 8.12 | 6.60 | 5.05 | 127.2 |
| **Total revenue** | **16.94** | **17.36** | **17.85** | **18.30** | **18.42** | **18.44** | **18.52** | **18.67** | **18.92** | **19.21** | **19.35** | **202.0** |

**Table 4-18: Evaluation Case 1 sensitivity: cumulative discounted cash flow, middle scenario revenue minus 15%, £ million, Central London**

| | 2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 | 2029 | 2030 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **D-RAN** | 6.53 | 10.34 | 13.34 | 16.05 | 17.61 | 19.43 | 20.77 | 20.37 | 18.48 | 14.66 | 9.59 |
| **C-RAN** | 7.11 | 11.52 | 14.60 | 17.18 | 18.71 | 20.24 | 21.44 | 19.91 | 17.44 | 13.86 | 7.74 |

**Table 4-19: Evaluation Case 1 sensitivity: summary financial measures, middle scenario revenue minus 15%, £ million, Central London**

| | NPV £ million | Indicative ROI |
|---|---|---|
| **D-RAN** | 9.59 | 2% |
| **C-RAN** | 7.74 | 0% |

***Revenues reduced by 30% across the board***

**Table 4-20: Evaluation Case 1 sensitivity: cost and revenue results combined, middle scenario revenue minus 30%, £ million, Central London**

| | 2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 | 2029 | 2030 | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **D-RAN access cost** | 6.61 | 8.43 | 9.15 | 9.51 | 10.40 | 10.09 | 10.48 | 12.27 | 14.08 | 16.65 | 18.62 | 126.3 |
| **C-RAN access cost** | 6.24 | 8.03 | 9.09 | 9.62 | 10.42 | 10.35 | 10.62 | 13.41 | 14.70 | 16.38 | 19.94 | 128.8 |
| **D-RAN full cost** | **10.41** | **13.28** | **14.42** | **14.98** | **16.38** | **15.90** | **16.51** | **19.32** | **22.17** | **26.22** | **29.33** | **198.9** |
| **C-RAN full cost** | **9.82** | **12.64** | **14.32** | **15.15** | **16.41** | **16.29** | **16.73** | **21.12** | **23.16** | **25.80** | **31.40** | **202.9** |
| **eMBB revenues** | 0.47 | 1.07 | 2.04 | 3.20 | 4.28 | 5.40 | 6.45 | 7.60 | 8.89 | 10.38 | 11.78 | 61.6 |
| **Legacy MBB revenues** | 16.36 | 16.06 | 15.38 | 14.42 | 13.22 | 11.89 | 10.69 | 9.45 | 8.12 | 6.60 | 5.05 | 127.2 |
| **Total revenue** | **16.83** | **17.13** | **17.42** | **17.62** | **17.50** | **17.28** | **17.14** | **17.04** | **17.01** | **16.98** | **16.83** | **188.8** |

**Table 4-21: Evaluation Case 1 sensitivity: cumulative discounted cash flow, middle scenario revenue minus 30%, £ million, Central London**

| | 2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 | 2029 | 2030 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **D-RAN** | 6.43 | 10.02 | 12.64 | 14.80 | 15.66 | 16.65 | 17.07 | 15.65 | 12.65 | 7.62 | 1.27 |
| **C-RAN** | 7.01 | 11.20 | 13.91 | 15.92 | 16.75 | 17.46 | 17.73 | 15.20 | 11.62 | 6.82 | -0.58 |

**Table 4-22: Evaluation Case 1 sensitivity: summary financial measures, middle scenario revenue minus 30%, £ million, Central London**

| | NPV £ million | Indicative ROI |
|---|---|---|
| **D-RAN** | 1.27 | -5% |
| **C-RAN** | -0.58 | -7% |

#### 4.1.2.2 Conclusions on the business case

Our first conclusion is that the baseline scenario in Evaluation Case 1 gives a positive business case for eMBB. Moreover, deploying a C-RAN network appears to make little difference to the business case compared to a D-RAN network.

However, the sensitivities we have conducted suggest that the baseline result which returns a positive business case is sensitive to the assumptions we have made around the evolution of ARPS for eMBB services and the growth of traffic. This can be seen from the figures for ROI Table 4-23.

**Table 4-23: Evaluation Case 1: comparison of ROI by sensitivity, Central London**

| | Baseline | Low revenue, low traffic | High revenue, high traffic | Baseline revenue - 15% | Baseline revenue - 30% |
|---|---|---|---|---|---|
| **D-RAN** | 8% | 31% | -11.5% | 2% | -5% |
| **C-RAN** | 6% | 35% | -11.9% | 0% | -7% |

There is a lack of consensus in the industry today over the prospects for 5G services, particularly over revenues. As we have discussed above, some studies show that consumers may be prepared to pay more for significant changes in mobile broadband performances, but on the other hand, mobile telecoms revenues have been flat over the last three years in the UK and many commentators are pessimistic over the prospects that 5G will lead to increases in ARPS.

We also reiterate that in less densely populated areas than Central London, the business case is likely to be worse. As a result, we conclude that there may be significant risks in deploying a stand alone, single tenant 5G NORMA network to support eMBB services.

#### 4.1.2.3 Business case for eMBB with multi-tenancy

The tables below present the business case calculations for our multi-tenancy scenario. We compare the financial implications for two separate network operators providing eMBB services with two tenants sharing a joint network to provide eMBB. The combined market share of the operators or tenants in each scenario is 36%.

**Table 4-24: Evaluation Case 2: cost and revenue results combined, middle scenario, £ million, Central London**

| | 2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 | 2029 | 2030 | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **2 networks access cost** | 13.57 | 15.63 | 17.63 | 19.80 | 19.58 | 21.49 | 21.38 | 25.35 | 29.48 | 33.76 | 39.42 | 257.1 |
| **2 sharing access cost** | 13.83 | 14.78 | 16.32 | 18.08 | 18.17 | 19.21 | 19.68 | 21.97 | 24.85 | 24.29 | 31.01 | 222.2 |
| **2 networks full cost** | **21.37** | **24.62** | **27.77** | **31.19** | **30.85** | **33.85** | **33.67** | **39.93** | **46.44** | **53.17** | **62.09** | **404.9** |
| **2 sharing full cost** | **21.79** | **23.28** | **25.70** | **28.47** | **28.61** | **30.25** | **31.00** | **34.61** | **39.14** | **38.26** | **48.85** | **350.0** |
| **eMBB revenues** | 1.35 | 3.07 | 5.82 | 9.15 | 12.23 | 15.42 | 18.44 | 21.71 | 25.40 | 29.67 | 33.66 | 175.9 |
| **Legacy MBB revenues** | 32.72 | 32.11 | 30.76 | 28.83 | 26.45 | 23.77 | 21.38 | 18.89 | 16.24 | 13.20 | 10.09 | 254.4 |
| **Total revenue** | **34.07** | **35.18** | **36.58** | **37.98** | **38.68** | **39.19** | **39.82** | **40.60** | **41.64** | **42.87** | **43.75** | **430.4** |

**Table 4-25: Evaluation Case 2: cumulative discounted cash flow, middle scenario, £ million, Central London,**

| | 2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 | 2029 | 2030 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **2 networks** | 12.71 | 22.57 | 30.26 | 35.81 | 41.78 | 45.59 | 49.69 | 50.11 | 47.32 | 41.72 | 32.39 |
| **2 sharing, 1 network** | 12.29 | 23.41 | 32.91 | 40.67 | 48.35 | 54.73 | 60.60 | 64.33 | 65.79 | 68.29 | 65.70 |

**Table 4-26: Evaluation Case 2: summary financial measures, middle scenario, £ million, Central London**

| | NPV £ million | Indicative ROI |
|---|---|---|
| **2 networks** | 32.39 | 6% |
| **2 sharing, 1 network** | 65.70 | 23% |

#### 4.1.2.4 Conclusions on the business case

These results show that there is a significant financial benefit from 5G NORMA's multi-tenancy innovation. The indicative results for ROI and NPV are significantly more positive in the 2 operator sharing one network scenario than in the two network scenario. Multi-tenancy appears to lead to a significant lessening of the potential risks we identified in Evaluation Case 1 to a single tenant deployment of eMBB.

## 4.2 Vehicle to everything services (V2X)

Vehicle to everything communications (V2X) is a collective term for services that involve any communication with a vehicle, either as source or destination, and includes several special cases such as vehicle to vehicle (V2V); vehicle to infrastructure (V2I) i.e. road infrastructure which may or may not be co-located with cellular infrastructure; vehicle to network (V2N); and vehicle to pedestrian (V2P).

We have identified three separate market segments with differences in the underlying network functionality requirements. The first, "connected vehicle infotainment", is essentially in vehicle eMBB, e.g. for non-real-time information on local amenities and road conditions, and entertainment or content for passengers such as video and social media.

The other two services fall under V2I and provide different degrees of driver assistance and automation. They fit within the 6 levels of vehicular automation put forward by the US Society of Automotive Engineers [Sea14] which are generally accepted in the automotive industry. Arguably, the need for critical MTC functionality increases the more autonomous a vehicle becomes, assuming that on-board systems cannot be used in isolation for more autonomous vehicles[11]. We call the two market segments:

- Assisted driving; and
- Semi-automated driving.

These two segments reflect our view that services towards the lower end of the autonomous driving scale will be brought to market first because consumer acceptance will be more forthcoming, regulatory barriers lower and technology more quickly available. Car makers such as Audi and Jaguar are already building basic applications such as route planning and parking into their in-vehicle services.

Semi-automated driving will be offered later than the more basic assisted driving service and we have modelled a transition from one to the other as early users of the basic version upgrade as well as new users coming on-stream. V2I services will be used as part of the vehicle's range of systems for lateral (lane-changing) and longitudinal assisted driving services. Both services will require high priority and high reliability hence they are classed as uMTC, however the semi-automated requirements will be greater.

We do not consider that full automation will have a great impact in this time period because the complicated regulatory issues may take time to resolve.

### 4.2.1 V2X revenue forecasts

Connected cars will be a major new source of revenue for the economy. Our forecasts are consistent with existing research such as the GSMA forecasts, e.g. [Gsm13] foresaw an overall European market of €4.1 billion for connectivity by 2018 (€40 billion in total including hardware, telematics and in-vehicle services) and the EC study [Ec15] which predicted EU consumer benefits of €22.7 billion per annum in 2030.

#### 4.2.1.1 Service take-up by segment

For V2X services, we defined the service take-up as the proportion of vehicles in Central London in the busy hour who subscribe to the service. [Mac15] estimates that there are 2,600 vehicles per square km in urban areas in the busy hour. We multiplied this by the area of our Central London region to estimate the total number of vehicles.

We modelled service take-up by the use of saturation curves. This models commonly observed patterns in how the rate of growth varies over a product's lifetime from initial acceleration, to a slowing down as maturity is reached. We also checked our forecasts against other sources such as [Kpm15] and found them to be consistent.

For the connected vehicles infotainment segment, we set the parameters of the saturation curve using the historic uptake of satellite navigation devices as a benchmark. The two assisted/automated driving services are substitutes for one another hence we model a saturation curve for both segments combined and then model a transition from assisted to semi-automated driving.

We expect take-up in the connected vehicle infotainment segment to be faster than the combined assisted driving segments. Assisted/automated driving requires an embedded device, hence take-up depends on churn of the vehicle itself whereas in-vehicle infotainment can be accessed via the handset which has a shorter churn period.

[11] However, some argue that fully autonomous vehicles should not need to rely on access to wireless networks.

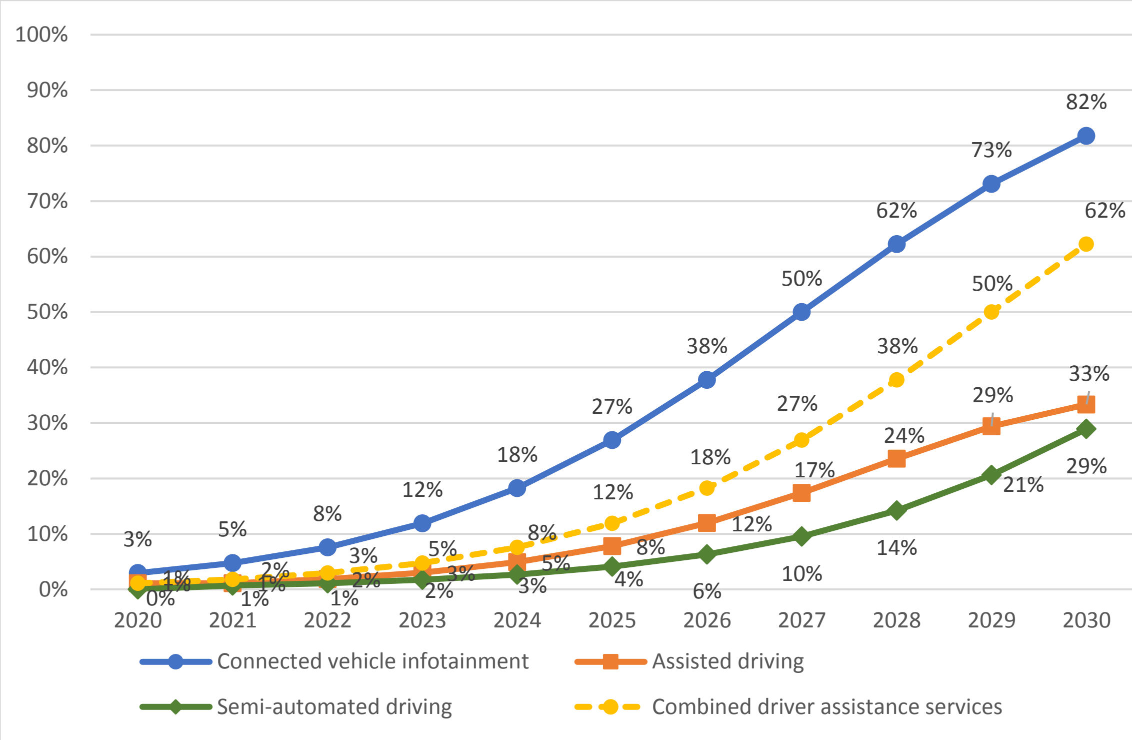



**Figure 4-1: Graph of V2X predicted take-up**

#### 4.2.1.2 ARPS by Market Segment

The three V2X market segments we have identified are in their early stages of development and evidence on what consumers are willing to pay is limited. Hence, we have looked to appropriate analogous services for indications of the value of these new services to consumers. As with other services, we have modelled three scenarios because of these uncertainties.

Connected vehicle infotainment: 5G ARPS is modelled as an uplift on third party revenue forecasts for an equivalent 4G infotainment service in 2018 including connectivity plus 10% of entertainment revenues from [Gsm13].

For assisted/automated driving, we use an indirect means to calculate the value of increased safety to the driver. First, we assume that the services could reduce vehicle insurance premiums. Currently, on-board driver monitoring devices (so-called *black box insurance*) commonly claim to offer a 30% saving. Insurance premiums could fall by more than this because assisted/automated driving should have a greater impact on accidents than the *black box insurance* devices. On the other hand, the benefit should be shared between end-users and service providers. The end-user would also benefit from greater convenience, increased fuel efficiency, reduced travel times and from avoiding the non-reimbursable costs of an accident such as time and inconvenience.

As a result, we assume an ARPS of 18% and 30% of the average UK car insurance premium for assisted driving and semi-automated driving respectively (in the middle scenario). We flex these assumptions up and down for the low and high scenarios for ARPS as shown in the table below.

**Table 4-27: Annual ARPS (£)**

| | Low Scenario | Middle Scenario | High Scenario |
|---|---|---|---|
| | 5G | 5G | 5G |
| Connected vehicle infotainment | 83 | 91 | 99 |
| Assisted driving | 122 | 133 | 156 |
| Semi-automated driving | 185 | 222 | 296 |

### 4.2.1.3 V2X revenue forecasts

Our revenue forecasts for the Central London area and the UK are presented in the two tables below.

**Table 4-28: 5G revenues V2X, UK – (£ million)**

| | 2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 | 2029 | 2030 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Connected vehicle infotainment | 95 | 154 | 246 | 387 | 592 | 873 | 1,226 | 1,623 | 2,021 | 2,373 | 2,654 |
| Assisted driving | 52 | 52 | 87 | 144 | 234 | 371 | 567 | 824 | 1,119 | 1,397 | 1,583 |
| Semi-automated driving | 0 | 56 | 87 | 136 | 210 | 325 | 498 | 755 | 1,123 | 1,629 | 2,288 |
| **Total: Middle** | **147** | **262** | **420** | **666** | **1,037** | **1,569** | **2,291** | **3,202** | **4,262** | **5,399** | **6,525** |
| | | | | | | | | | | | |
| **Total: low** | **134** | **234** | **376** | **597** | **928** | **1,405** | **2,049** | **2,860** | **3,798** | **4,795** | **5,770** |
| **Total high** | **165** | **303** | **486** | **771** | **1,200** | **1,819** | **2,663** | **3,738** | **5,007** | **6,391** | **7,792** |

**Table 4-29: V2X: 5G revenues V2X, Central London – (£ million)**

| | 2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 | 2029 | 2030 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Connected vehicle infotainment | 0.3 | 0.4 | 0.7 | 1.0 | 1.6 | 2.3 | 3.3 | 4.3 | 5.4 | 6.3 | 7.1 |
| Assisted driving | 0.1 | 0.1 | 0.2 | 0.4 | 0.6 | 1.0 | 1.5 | 2.2 | 3.0 | 3.7 | 4.2 |
| Semi-automated driving | 0.0 | 0.1 | 0.2 | 0.4 | 0.6 | 0.9 | 1.3 | 2.0 | 3.0 | 4.3 | 6.1 |
| **Total: Middle** | **0.4** | **0.7** | **1.1** | **1.8** | **2.8** | **4.2** | **6.1** | **8.5** | **11.4** | **14.4** | **17.4** |
| | | | | | | | | | | | |
| **Total: low** | **0.4** | **0.6** | **1.0** | **1.6** | **2.5** | **3.7** | **5.5** | **7.6** | **10.1** | **12.8** | **15.4** |
| **Total high** | **0.4** | **0.8** | **1.3** | **2.1** | **3.2** | **4.9** | **7.1** | **10.0** | **13.4** | **17.0** | **20.8** |

## 4.2.2 Business case for V2X

The tables below summarise the results of our business case analysis for V2X services in the context of Evaluation Case 3, i.e. they model a multi-service network with different combinations of eMBB plus the three V2X services that we modelled. The eMBB only single tenant network costs on which the Evaluation Case 3 results are built upon are slightly higher than the corresponding eMBB costs used in Evaluation Case 1 (by about 7%). As described in Section 0 for the Evaluation Case 3 cost analysis a wider search radius was applied in the network dimensioning tool to later accommodate non-eMBB services with large cell ranges in this case which has caused this difference in baseline eMBB network used for Evaluation Cases 1 and 3 and resulting difference in cost base.

We assumed that the market share for eMBB services is 18% and for all the other services 100% following the assumptions that were used in the cost model. The eMBB market share is based on the current market share of representative UK mobile operators. We assumed 100% market share for other services because, in the Central London study area at least, one MNO is assumed to have engaged with the tenants considered (i.e. city council, energy providers etc.) and to have 100% market share for these services.

**Table 4-30: Evaluation Case 3: V2X cost and revenue results combined, middle scenario £ million, Central London**

| | 2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 | 2029 | 2030 | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Full costs: eMBB plus service as indicated** | | | | | | | | | | | | |
| **eMBB only** | 11.85 | 12.13 | 13.74 | 14.52 | 15.88 | 15.74 | 17.04 | 19.16 | 22.60 | 31.25 | 31.19 | 205.1 |
| **Semi-automated driving** | 11.85 | 11.93 | 13.28 | 14.33 | 15.36 | 15.85 | 16.59 | 19.54 | 22.21 | 30.08 | 33.15 | 204.2 |
| **Assisted driving** | 11.85 | 11.93 | 13.57 | 14.73 | 16.26 | 16.79 | 16.39 | 19.40 | 28.28 | 26.69 | 34.16 | 210.0 |
| **Vehicle infotainment** | 12.18 | 12.29 | 14.62 | 15.18 | 16.93 | 17.97 | 17.52 | 21.19 | 27.43 | 30.74 | 35.68 | 221.7 |
| **Full revenues: eMBB plus service as indicated** | | | | | | | | | | | | |
| **eMBB only** | 17.04 | 17.59 | 18.29 | 18.99 | 19.34 | 19.60 | 19.91 | 20.30 | 20.82 | 21.43 | 21.88 | 215.2 |
| **Semi-automated driving** | 17.04 | 17.74 | 18.52 | 19.35 | 19.90 | 20.46 | 21.24 | 22.31 | 23.82 | 25.78 | 27.98 | 234.1 |
| **Assisted driving** | 17.18 | 17.73 | 18.52 | 19.37 | 19.96 | 20.59 | 21.42 | 22.50 | 23.81 | 25.16 | 26.10 | 232.3 |
| **Vehicle infotainment** | 17.29 | 18.00 | 18.95 | 20.02 | 20.92 | 21.93 | 23.18 | 24.63 | 26.21 | 27.76 | 28.95 | 247.8 |

**Table 4-31: Evaluation Case 3: V2X cumulative discounted cash flow, middle scenario, £ million, Central London,**

| | 2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 | 2029 | 2030 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **eMBB only** | 5.19 | 10.29 | 14.26 | 17.91 | 20.55 | 23.29 | 25.20 | 25.91 | 24.88 | 19.54 | 14.81 |
| **eMBB & Semi-automated driving** | 5.19 | 10.62 | 15.20 | 19.29 | 22.75 | 26.05 | 29.14 | 30.87 | 31.81 | 29.47 | 26.84 |
| **eMBB & Assisted driving** | 5.33 | 10.75 | 15.08 | 18.87 | 21.70 | 24.40 | 27.76 | 29.69 | 27.09 | 26.25 | 22.16 |
| **eMBB & Vehicle infotainment** | 5.11 | 10.45 | 14.23 | 18.18 | 21.23 | 24.05 | 27.81 | 29.96 | 29.25 | 27.62 | 24.20 |

**Table 4-32: Evaluation Case 3: V2X summary financial measures, middle scenario £ million, Central London**

| | NPV £ million | Indicative ROI |
|---|---|---|
| **eMBB only** | 14.81 | 5% |
| **eMBB & Semi-automated driving** | 26.84 | 15% |
| **eMBB & Assisted driving** | 22.16 | 11% |
| **eMBB & Vehicle infotainment** | 24.20 | 12% |

#### 4.2.2.1 Conclusions on the business case

The results suggest that deploying a multi-service network comprising eMBB plus any of the three V2X services modelled may lead to moderate but significant improvements in the overall business case. They also help to lessen the potential risks we identified in Evaluation Case 1 to a standalone deployment of eMBB but do not completely remove them (i.e. costs still outstrip revenues by 2028 in these eMBB plus one of the V2X services cases compared with by 2027 in the eMBB only case).

The biggest improvement comes from providing eMBB together with the semi-automated driving, though the other categories are not far behind.

An area for further research would be to consider the impact of a multi-service offer consisting of eMBB and various combinations of the V2X services, rather than each on its own.

## 4.3 Smart city services

Smart cities have the potential to generate significant value for consumers and society. Already, many cities around the world have launched various smart city initiatives and used existing technologies and we expect these uses to broaden and widen as the capabilities of mobile communications networks improve (through proprietary technologies, LTE and 5G).

Smart city services, i.e. those commissioned by city and municipal authorities, typically fall into the following categories:

- Intelligent transport systems – providing information on road conditions, automated control of signals and signage, routing to avoid congestion, accident response etc. They may cover all types of road users including motor vehicles, bicycles and pedestrians;
- Smart energy – smart metering, support for microgeneration and smart grids;
- Smart water and sewerage – improved infrastructure management and maintenance using sensors to provide more accurate and more timely information on the physical state of the network (e.g. leaks), flows, congestion and load balancing;
- Environmental monitoring – the use of sensors to schedule household refuse collections, measurement of landfill toxicity, monitoring of pollution and emissions across industry and road usage to inform environmental strategy and for public health planning;
- Public sector services – including emergency services. Waste collection is sometimes included in this category;
- Intelligent buildings – this includes building automation, surveillance and security.

We have focused on the first three categories which we believe capture the majority of, though not all, smart city revenues. Our reasons for this were because we found that use cases were better defined for these categories and that consequently more evidence and data was available on which to forecast revenues.

### 4.3.1 Smart city revenue forecasts

#### 4.3.1.1 Intelligent transport systems

We based our revenue estimates for intelligent transport systems on data from London's transportation authority Transport for London (TfL) and compared the spending to data on ITS spending in Copenhagen and Rio de Janeiro to confirm that the London data was representative.

TfL has commissioned a "surface intelligent transport system" to replace its existing systems of cameras (supporting its congestion charging system) and road infrastructure. The main elements, as detailed in [Tfl15], comprise computerised control of traffic lights, predictive signalling to improve traffic flow, amelioration of bus and cycle flows and faster accident response.

For the Central London area, we assume that the service will have been deployed by 2020 so the initial take-up is 100%. The designers of the actual London system will be making technology choices as the network is rolled out over the next 5 years and the choice of technology is uncertain, but may include plans for migrating from existing technologies to 5G. In any case the perspective of this analysis is to illustrate the potential of using the 5G NORMA architecture for ITS. Across the UK, cities and towns will deploy these services at different rates, so we model the penetration of the UK population using a saturation curve methodology, with the same rate of take-up as logistics (see Section 4.4).

**Table 4-33: Penetration forecast for ITS**

| | 2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 | 2029 | 2030 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **ITS penetration** | 3% | 5% | 8% | 12% | 18% | 27% | 38% | 50% | 62% | 73% | 82% |

We annualise the operational costs (as opposed to start up costs which we believe mainly relate to non-telecoms related costs such as the IT systems for traffic management) of the TfL scheme over its 21-year lifetime and then calculate the cost per head of population. We assume that 5G ARPU will be moderately higher than the costs of the current contract. This translates into a 5%, 10% and 20% uplift for the low, middle and high 5G revenue scenarios.

#### 4.3.1.2 Smart energy

In many western countries, the use of smart communications technology to manage more efficiently energy supply and usage has become an integral part of national energy strategies. In particular, the challenges of moving to a low(er) carbon economy, the long term upward cost trend of carbon based energy sources and occasional capacity constraints in some countries have led governments to back smart energy:

- Smart meters are a way smoothing peak energy demands in the short term: they stimulate changes in behaviour by making consumers more aware of energy usage during the course of the day. It is hoped this will lead consumers to switch non-time critical energy usage to times of day when demand, and prices, are lower; and
- Smart grids are expected to be an essential part of the longer term transition to lower carbon energy, particularly by enabling decentralised energy networks. They are expected to accommodate more diverse and local energy generation, cope with the different patterns of renewable generation and allow energy suppliers dynamically to adjust energy usage (with the customer's permission) at times of high demand.

Smart meter deployments are already well underway in some countries, but progress differs. For example, some countries such as Finland, Italy and Sweden had achieved 100% deployment in electricity by 2014. The UK has a target of 100% smart meter deployment for electricity and gas by 2020. In contrast, Germany is aiming only to deploy smart meters where economically justified. The EC's Institute for Energy and Transport, Smart Grid Projects Outlook 2014, expects a deployment of 72% by 2020 across the EU in the electricity sector [Jrc14].

The emerging business model for smart meters and grids appears to be that energy utilities, singly or on an industry-wide basis, agree long term contracts for the communications services. For example, in the UK, Arqiva and O2 won the contracts for these services. Therefore, we have modelled a single industry customer covering the whole of the UK (or a part thereof).

#### 4.3.1.3 Smart energy take-up by segment

**Smart meters** – We take as a given that the UK will achieve its aim of 100% rollout of smart meters by 2020 when our forecasting period starts.

**Smart grids** – We use a saturation curve approach to forecast the rising density of smart grid communications deployment which should evolve in line with the changing nature of energy supply. Given these long term developments, we believe it is reasonable to assume a steady increase in penetration over the decade to 2030 which is similar to those we predict for other 5G services. Our take-up forecast is shown in Table 4-34.

**Table 4-34: Smart grid predicted take-up**

| | 2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 | 2029 | 2030 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Smart Meters** | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% |
| **Smart Grid** | 4% | 6% | 10% | 14% | 21% | 29% | 39% | 50% | 61% | 71% | 79% |

#### 4.3.1.4 Smart energy ARPS

**Smart meters** – We used the O2 and Arqiva contract figures to estimate annual revenue for smart meters (electricity and gas). The total contract values were £2.1 billion (undiscounted) over 15 years which is a straight average of £140mn per annum [Tel13].

In order to reflect uncertainty over the differences between 5G and legacy technologies, we assume that 5G NORMA functionality brings modest additional benefits for smart meters leading to an uplift of 5%, 10% and 20% in our low, middle and high scenarios of the legacy contract value.

**Smart grids** – ARPS was calculated as follows. [Ear12] estimated the total costs of an electricity smart grid system for the UK, broken down by inputs. Communications was estimated at 14% of spending. Therefore communications spend was equivalent to an annual spend of £140 million pa over the 38 year project lifetime. We assumed another 50% to cover smart gas grid needs (on the basis that the requirements for electricity seem more extensive). This took the total annualised spend to £220 million. ARPS in the low and high scenarios is varied by +/-10% as shown in Table 4-35.

**Table 4-35: ARPS for smart meters and grids, 2020: subscriber = whole energy industry (£ million)**

| | Low Scenario | Middle Scenario | High Scenario |
|---|---|---|---|
| | 5G | 5G | 5G |
| **Smart Meters** | 144 | 151 | 164 |
| **Smart Grid** | 200 | 223 | 244 |

#### 4.3.1.5 Smart water

We took a high level approach to modelling the revenue opportunity for smart water and sewerage management because of the lack of data for a more detailed prediction. Essentially we assume that smart water and sewerage will have similar needs as for smart energy (meters and grids). Therefore, we assume that ARPS (4G and 5G) will vary in line with the turnover of the water and energy distribution sectors. We assume that penetration of these services will follow the same evolution in penetration as smart grids.

#### 4.3.1.6 Smart city revenue results

Our revenue forecasts for the Central London area and the UK are presented in the two tables below.

**Table 4-36: 5G revenues Smart Cities, UK – (£ million)**

| | 2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 | 2029 | 2030 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Intelligent Transport System** | 2 | 3 | 5 | 8 | 13 | 19 | 27 | 35 | 44 | 52 | 59 |
| **Smart meters** | 151 | 163 | 177 | 179 | 187 | 194 | 198 | 200 | 199 | 203 | 207 |
| **Smart grid** | 9 | 14 | 21 | 32 | 46 | 64 | 87 | 111 | 136 | 158 | 177 |
| **Smart water** | 5 | 7 | 11 | 16 | 24 | 34 | 46 | 59 | 73 | 85 | 95 |
| **Total: Middle** | **167** | **187** | **214** | **235** | **269** | **311** | **357** | **405** | **452** | **498** | **538** |
| | | | | | | | | | | | |
| **Total: low** | **159** | **178** | **203** | **223** | **254** | **293** | **337** | **381** | **424** | **467** | **504** |
| **Total high** | **181** | **203** | **232** | **255** | **291** | **335** | **384** | **435** | **484** | **532** | **574** |

**Table 4-37: 5G revenues Smart Cities, Central London – (£ million)**

| | 2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 | 2029 | 2030 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Intelligent Transport System** | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 | 0.4 |
| **Smart meters** | 0.9 | 1.0 | 1.1 | 1.1 | 1.2 | 1.2 | 1.2 | 1.2 | 1.2 | 1.2 | 1.3 |
| **Smart grid** | 0.1 | 0.1 | 0.1 | 0.2 | 0.3 | 0.4 | 0.5 | 0.7 | 0.8 | 1.0 | 1.1 |
| **Smart water** | 0.0 | 0.0 | 0.1 | 0.1 | 0.1 | 0.2 | 0.3 | 0.4 | 0.4 | 0.5 | 0.6 |
| **Total: Middle** | **1.4** | **1.6** | **1.7** | **1.8** | **2.0** | **2.2** | **2.5** | **2.7** | **3.0** | **3.2** | **3.4** |
| | | | | | | | | | | | |
| **Total: low** | **1.4** | **1.5** | **1.6** | **1.7** | **1.9** | **2.1** | **2.3** | **2.6** | **2.8** | **3.0** | **3.2** |
| **Total high** | **1.5** | **1.7** | **1.8** | **2.0** | **2.2** | **2.4** | **2.6** | **2.9** | **3.2** | **3.4** | **3.6** |

## 4.3.2 Business case for smart city services

In this section, we consider the business cases for eMBB plus smart city services. This is part of Evaluation Case 3. We only consider smart meters from the wider range of smart city services. This is because we expected the impact of intelligent transport systems and smart water on costs to be relatively minor compared to other services, so the costs have not been modelled. Our revenue forecasts for intelligent transport systems and smart water were lower than for smart meters, but are not insignificant. Therefore, they are likely to add upside to the business case if the costs as well as the revenues are modelled. As with the V2X business case, we assumed that the market share for eMBB services is 18% and for all the other services 100%.

**Table 4-38: Evaluation Case 3: smart city cost and revenue results combined, £ million, Central London**

| | 2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 | 2029 | 2030 | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Full costs: eMBB plus service as indicated** | | | | | | | | | | | | |
| **eMBB only** | 11.85 | 12.13 | 13.74 | 14.52 | 15.88 | 15.74 | 17.04 | 19.16 | 22.60 | 31.25 | 31.19 | 205.1 |
| **Smart meters** | 19.84 | 12.54 | 13.07 | 14.39 | 14.70 | 14.61 | 15.12 | 17.19 | 22.90 | 30.72 | 41.19 | 216.3 |
| **Full revenues: eMBB plus service as indicated** | | | | | | | | | | | | |
| **eMBB only** | 17.04 | 17.59 | 18.29 | 18.99 | 19.34 | 19.60 | 19.91 | 20.30 | 20.82 | 21.43 | 21.88 | 215.2 |
| **Smart meters** | 18.02 | 18.68 | 19.51 | 20.29 | 20.78 | 21.20 | 21.67 | 22.22 | 22.89 | 23.65 | 24.24 | 233.1 |

**Table 4-39: Evaluation Case 3: smart city cumulative discounted cash flow, middle scenario, £ million, Central London,**

| | 2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 | 2029 | 2030 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **eMBB only** | 5.19 | 10.29 | 14.26 | 17.91 | 20.55 | 23.29 | 25.20 | 25.91 | 24.88 | 19.54 | 14.81 |
| **Smart meters** | -1.82 | 3.92 | 9.54 | 14.36 | 19.00 | 23.70 | 28.06 | 31.20 | 31.19 | 27.35 | 18.73 |

**Table 4-40: Evaluation Case 3: smart city summary financial measures, £ million, Central London**

| | NPV £ million | Indicative ROI |
|---|---|---|
| **eMBB only** | 14.81 | 5% |
| **Smart meters** | 18.73 | 8% |

### 4.3.2.1 Conclusions on the business case

The results suggest that deploying a multi-service network comprising eMBB and smart meters would lead to a small improvement in the overall business case and help to lessen the potential risks we identified in Evaluation Case 1 to a standalone deployment of eMBB.

It is likely that the inclusion of other smart city services, such as intelligent transport systems and smart water, would increase the extent to which these smart city multi-service scenarios improve the business case.

## 4.4 Logistics

We have only modelled the revenues for logistics services. Similar to intelligent transport systems and smart water, we have not modelled the costs of supporting logistics services on a 5G NORMA network. This is because we expected the costs to be relatively minor compared to other services. As before, full consideration of the costs and revenues of logistics is likely to add upside to the business case in a multi-service situation.

In making revenue forecasts for logistics, we consider a vehicular mMTC service for use in road haulage, i.e. the transport of goods by road. Sensors could measure various data including: location for tracking; temperature and humidity; vehicle loading and driver performance. Similar services could be provided for rail freight, but here we focused on road haulage. The footprint of rail freight is different to road and it might make more sense to be considered as part of an analysis of wider service for the rail industry.

Logistics has a Business to Business (B2B) component, i.e. enabling the haulage company to improve efficiency and increase average vehicle loading, and to assure driver safety. It also has a Business to Business to Consumer (B2B2C) component. Delivery companies can provide enhanced information about consignment delivery beyond location (as provided by GPS tracking today) and enable corrective action to be taken, e.g. if the temperature rises above/below specified limits.

We model revenues for the service based on the potential increase in value from more efficient vehicle loading. We were unable to find sufficiently robust information to assess the other elements during this project. However, they would certainly add an upside to our revenue forecasts and further study would be a useful exercise in this area. The stages are as follows:

- Calculate the value from the maximum possible increase in efficiency;
- Attribute a portion of that increase to 5G NORMA;
- Estimate the total potential increase in efficiency based on the [Ec15] methodology for the maximum potential efficiency improvement.
    - 30% of freight vehicles run empty and the loading or utilisation of the remainder is 68% according to [Ons16]. This gives a potential 52% increase in efficiency. Following [Ec15], we assume that half this results from exogenous factors, so the total potential efficiency improvement is 26%.
- Estimate the proportion of the maximum efficiency improvement that 5G can generate based on [Ec15]. We apply this to the middle scenario and flex the others around this. Thus, we conservatively assume that the impact of 5G is 1.5%, 2% and 2.5% of the maximum 26% efficiency improvement for the low, middle and high scenarios.

The resulting 5G impact percentage is applied to the total value of the UK road freight sector [Ons17] to derive the total value of the potential 5G impact.

We estimate the impact for Central London by adjusting the UK impact pro rata to the total distance travelled (km) by freight vehicles in Central London relative to the UK, see [Tfl14] and [Ons16].

### 4.4.1 Logistics revenue forecasts

The table below presents our revenue forecasts for logistics services. In the study area of central London these are smaller compared to for example smart meters, see Section 4.3.2, thus revenues from logistics are not considered further.

**Table 4-41: 5G revenues Logistics, UK – (£ millions)**

| | 2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 | 2029 | 2030 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Logistics: middle** | 29 | 47 | 75 | 118 | 181 | 267 | 375 | 497 | 618 | 726 | 812 |
| | | | | | | | | | | | |
| **Logistics: low** | 22 | 35 | 56 | 89 | 136 | 200 | 281 | 372 | 464 | 544 | 609 |
| **Logistics high** | 36 | 59 | 94 | 148 | 226 | 334 | 469 | 621 | 773 | 907 | 1,015 |

**Table 4-42: 5G revenues Logistics, Central London – (£ millions)**

| | 2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 | 2029 | 2030 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Logistics: middle** | 0.3 | 0.5 | 0.9 | 1.4 | 2.1 | 3.1 | 4.3 | 5.7 | 7.1 | 8.4 | 9.4 |
| | | | | | | | | | | | |
| **Logistics: low** | 0.3 | 0.4 | 0.7 | 1.0 | 1.6 | 2.3 | 3.2 | 4.3 | 5.3 | 6.3 | 7.0 |
| **Logistics high** | 0.4 | 0.7 | 1.1 | 1.7 | 2.6 | 3.8 | 5.4 | 7.2 | 8.9 | 10.5 | 11.7 |

## 4.5 Summary of conclusions

Our conclusions on the business case for the 5G NORMA deployment modelled are as follows. Overall, the business case appears positive for the 2020 to 2030 time-frame of the model in the baseline scenario of Evaluation Case 1. Furthermore, deploying a C-RAN network appears to make little difference to the business case compared to a D-RAN network. However, there may be significant risks in deploying a stand-alone, single tenant 5G NORMA network to support eMBB as illustrated by the variation from positive to negative ROI in our sensitivity analysis of Evaluation Case 1.

Our analysis in Evaluation Case 2 suggest that a multi-tenancy deployment could lead to a significant lessening of the potential risks we identified in Evaluation Case 1 to a single tenant deployment of eMBB.

In comparison, the multi-service scenarios in Evaluation Case 3 appear to have a smaller impact on the business case than those in Evaluation Case 2. A multi-service network comprising eMBB and any one of the three V2X services we modelled leads to a moderate improvement in the overall business case and a lessening of the potential risks we identified in Evaluation Case 1 to a stand-alone deployment of eMBB. A network combining multiple V2X services and eMBB could have a more significant compound effect on the business case, however that was outside the scope of our cost modelling.

A multi-service network comprising eMBB and smart meters would lead to a small improvement in the overall business case and help to lessen the potential risks we identified in Evaluation Case 1 to a stand alone deployment of eMBB.

The impact of each of our Evaluation Cases on the ROI is summarised in Table 4-43 and Table 4-44, respectively.

**Table 4-43: Evaluation Case 1: comparison of ROI by sensitivity, Central London**

| | | NPV £ million | ROI |
|---|---|---|---|
| **Evaluation Case 1 (C-RAN)** | Baseline | 16.06 | 6% |
| | Low revenue, low traffic | 40.51 | 35% |
| | High revenue, high traffic | -9.26 | -11.9% |
| | Baseline revenue -15% | 7.74 | 0% |
| | Baseline revenue -30% | -0.58 | -7% |

**Table 4-44: Evaluation Case 2 and 3: Improvement in ROI relative to eMBB only by sensitivity, Central London**

| | | ROI |
|---|---|---|
| **Evaluation Case 2 (multi-tenancy)** | 2 sharing, 1 network | +17% |
| **Evaluation Case 3 (eMBB combined with …)** | Semi-automated driving | +10% |
| | Assisted driving | +6% |
| | Vehicle infotainment | +7% |
| | Smart meters | +3% |

# 5 Value Creation by 5G NORMA – assessment of social and wider economic benefits

This chapter looks at the wider value that could be created by 5G NORMA in addition to the direct economic value from providing communications services to end-users. This is important because, although the commercial business case is likely to be positive under most scenarios (as suggested by our indicative results in the previous chapter) there are risks in the longer term and if revenues do not meet expectations. Moreover, the business case in less densely populated areas is likely to be weaker than in the densely populated Central London area.

As a result, we consider whether the wider social and economic benefits that may be generated from 5G NORMA are significant. We then consider whether public sector intervention and/or partnership with the private sector may be useful in areas where the commercial business case is weak and in mitigating the risks to 5G NORMA deployment and make an initial analysis of the options for public intervention.

## 5.1 What is socio-economics?

In this section, we explain what is meant by the term socio-economics and why it is important to take such a perspective when considering value creation. We also look at why intervention by governments and regulators might be necessary to realise the full socio-economic potential of the 5G NORMA innovations.

Socio-economics concerns the creation of well-being and value. It includes the value created for individual consumers and businesses from economic activity, and collectively by issues that affect them all such as the environment they live in and the degree of social cohesion. Broadly speaking we can identify three main areas of value creation or the promotion of well-being:

- Direct private benefits - private benefits resulting from transactions in a market, such as buying a mobile subscription, are so-called because they concern only to the consumer and the producer and not to the wider public.
- Wider economic benefits - market transactions can generate secondary or indirect effects, which affect the economy or society. For example, if a mobile subscriber's friends all connect to a network, the value of her subscription increases even though she was not party to her friends' transactions since she can call her friends. Equally innovations, e.g. the invention of the light bulb, may open up opportunities in many different parts of the economy. Such indirect benefits are often difficult to predict but their impact can be profound. We believe that the 5G NORMA platform has great potential in this area:
    - 5G NORMA innovations, (along with other 5G innovations) may disrupt the mobile communications business and stimulate the potential for innovation in end-user applications and services. The economic value generated could be significant. A good analogy is touch screen technology which facilitated the iPhone and its followers. Without this the mobile Internet revolution and all the value it has created might have been very different. The potential for and implications of such market disruption are discussed in Chapter 6.
    - The other indirect benefit relates to the potential impact on business practices in the wider economy. For example, mobile phones create value in enabling communication on the move. In addition, economic studies have shown that mobile technology has also enabled companies to change the way they do business and hence has increased labour productivity.
- Public or societal benefits – these are benefits that do not arise from open market transactions. For example, everyone in society benefits from services that increase social inclusion and cohesion (even though they don't directly pay for them), e.g. because the risk of crime is reduced and there is a value to living in a fair society. Pollution is a

negative example, i.e. a social cost, because air pollution is a side-effect of some industrial processes which affects society as a whole rather than just the polluter and its customers.

It should be clear from the above that it is important to look beyond the narrow benefits from economic activity if we are to capture the full value of the 5G NORMA platform on the economy and society. We also hope that our approach will inform future techno-economic studies in the communications fields.

It is also important to consider the role of government given that the wider economic and social benefits may be significant in 5G NORMA. Governments are stakeholders by virtue of being major consumers in their own right and they have significant powers to influence social benefits and costs by setting regulations, taxes and subsidies.

The diagram below encapsulates the connections between government, private companies and consumers. It identifies three pillars of value creation: private benefits; common or social benefits; and political benefits[12]. It also identifies a positive feedback loop between well founded government policy and the well-being of both the private sector and society. This promotes political stability which promotes sound government policy and so on.

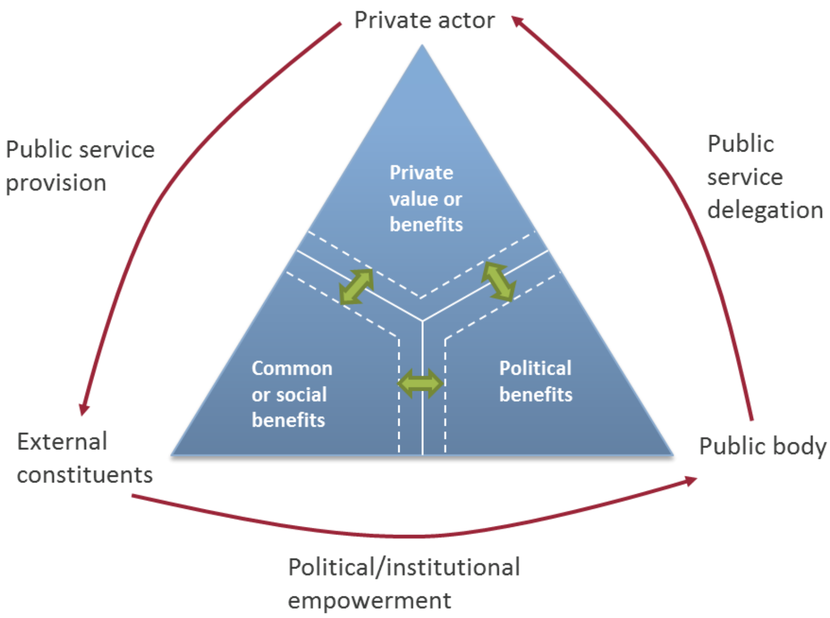



**Figure 5-1: The three pillars of value creation [KQ11]**

In the telecoms sector, regulation has long had to consider wider economic and social benefits. The provision of universal service is one example of how governments intervened in markets across the EU to improve societal well-being because of the role of telecoms in promoting social inclusion. Another example was the inclusion of the social benefits of television (e.g. maintaining informed citizens in cost-benefit evaluation of whether to switchover television broadcasting from analogue to digital and release spectrum for mobile communications [Ofc07]).

[12] Though political benefits are important because they affect how government objectives are decided, they are beyond the scope of our analysis.

## 5.2 The implications of wider economic and social benefits for value creation

We expect 5G NORMA to bring significant wider socio-economic benefits as stated above. A number of key themes have emerged in our research:

- Social benefits, particularly:
  - Improvement of the environment through reduction in greenhouse gas emissions;
  - Reduced congestion;
  - Reduced number of road fatalities; and
- Indirect economic benefits including:
  - Productivity; and
  - Innovation in end-user applications and services.

The table below shows how these themes relate to the key 5G services we have studied in our business case analysis presented in the previous chapter.

**Table 5-1: Socio-economic benefits arising from key 5G services**

| | Reduced carbon emissions | Reduced congestion | Reduced road fatalities | Productivity |
|---|---|---|---|---|
| **eMBB** | | | | ✓ |
| **Assisted driving / V2X** | ✓ | ✓ | ✓ | |
| **Smart meters** | ✓ | | | |
| **Intelligent transport systems** | ✓ | ✓ | ✓ | |
| **Smart water** | | | | ✓ |
| **Logistics** | ✓ | ✓ | | ✓ |
| **Industry 4.0**[13] | | | | ✓ |

However, since commercial investment decisions are made on the basis of the service providers' private values, there is a risk that the market fails to deliver all the socio-economic benefits that may be possible. This raises the question of how those additional benefits could be realised which is the subject of this chapter.

Ensuring that socio-economic benefits are maximised may also create a beneficial feedback-loop to the private sector (as shown in the three pillars of value diagram). Networks may be deployed more widely and average costs may fall due to increased economies of scale and scope. This may reduce barriers to investment thus increasing private sector value[14]. Hence, both the private sector and society can gain from public sector involvement and this may strengthen the case for government intervention in 5G.

Next, we consider the EU's views on public sector involvement, particularly in achieving the goals for the EU Digital Single Market programme, and the limits this implies for government intervention. We also look at the practical steps governments should consider in deciding how to intervene.

[13] This was not a central focus for the study and is only covered at a high level.

[14] If government intervention were insufficient the feedback-loop could go into reverse.

#### 5.2.1.1 There are ample EU precedents for intervention in telecoms to achieve social benefits.

The European Commission has publicly stated a preference for delivering 5G through the private sector and competitive markets, and that public intervention should be limited to rural and disadvantaged areas. However, the Commission has accepted since 2016 that there can be a role for public sector involvement in 5G beyond this. Intervention should still be limited however, and ideally should be time-limited and targeted.

The EC's Digital Agenda launched in August 2010 a significantly earlier round of public sector involvement in communications infrastructure. It called on Member States to use public financing to meet coverage, speed and take-up targets and spurred a lot of investment. Many governments favoured public private partnership (PPP) approaches, and focused on typically fibre based, high speed fixed access deployments. Many interventions were in so-called "white areas" where deployment was not commercially viable, e.g. due to low population density. Hence, the rationale was to achieve social benefits that the market could not deliver and this facilitated State Aid approval.

The EC launched the Digital Single Market initiative in May 2015 (as a successor to the Digital Agenda) and published a 5G Action Plan [Ec16a] as part of this in September 2016. The Action Plan set out a clear roadmap for public and private investment on 5G infrastructure in the EU. It focused on the role of the public sector as a consumer of mobile services and emphasised the need for the public sector to move quickly to adopt 5G.

An EC Communication, [EC16b], launched in parallel in September 2016, identified a number of areas are relevant to the issues of government intervention and PPP:

- Public intervention to promote 5G through subsidies can attract long-term private investment by mitigating short-term risks where the business case is positive in the long term. Hence, intervention could accelerate 5G deployment and enable operators to reach scale faster. This may lead to a virtuous circle if it leads to increased economies of scale. It may also facilitate wider geographic rollout of networks which may be important to certain use cases, e.g. smart energy and V2X, where widespread coverage is important.
- Promoting access to and take-up of very high capacity (Gigabit) connections is proposed as a legitimate regulatory objective. The public sector can influence this both as an end-user (e.g. schools and government bodies) and as a facilitator. There are clear wider economic benefits through the possible impact on productivity of Gigabit services. Moreover, if unit costs overall might fall, this would boost services (and their associated social benefits) such as smart energy which do not need Gigabit connectivity.
- Adapting regulatory models to favour more sharing in "areas where infrastructure-based competition may not be realistic" by allowing co-investment by rival operators and pooling of costs etc. Again, this could reduce unit costs of the whole platform and allow socially beneficial services to be deployed more extensively. We discuss this further in Chapter 6.

In addition, there are a number of other government and EU programmes, such as the transition to a low carbon economy, for which a high quality, ubiquitous, reliable mobile network will be one of several important elements. For that reason, it will be difficult to separate out the impact of mobile communications from these other elements, nonetheless governments should try to factor it into decisions on whether to intervene in 5G deployment.

Governments will be keen to ensure value for money in the use of public funds and that subsidies are given only where there is a clear risk of "market failure" i.e. where it is uneconomic for the private sector to provide services.

In general, our modelling suggests that the business case may be positive even in the baseline case for eMBB and should improve once the economies of scale and scope from the multi-tenancy and multi-service capabilities of 5G NORMA are taken into account. However, there is a risk that the business case turns negative if revenues are not as high as we predict in our baseline scenario, or if traffic grows more rapidly than we expect. Moreover, we would expect the business case to be worse in less densely populated areas than Central London, though we cannot verify this without modelling such areas which lie outside the scope of this study.

Governments will face uncertainty and informational disadvantages (compared to the private sector) in a number of areas, e.g.:

- Identifying the commercially viable level for private sector service provision;
- Evaluating the costs of extending service beyond the commercially viable level (or accelerating the timetable for launching new services); and
- Evaluating the social benefits from extending service beyond commercially viable levels.

It is clear that wide-spread network deployment is a pre-requisite for maximising the social benefits (net of costs) that 5G networks could generate over and above 4G networks. The same was true for next generation broadband where much intervention focused on rural coverage. In contrast, the focus for 5G will be on cities and suburbs[15] as well as rural because the social benefits, such as reduced pollution, will be more widespread. However, intervention, if it is necessary in more densely populated areas, is likely to be more targeted and limited than in rural areas.

#### 5.2.1.2 Regulators should choose carefully the mechanisms for supporting infrastructure deployment

As the three pillars of value diagram showed, the interaction between the public and private sector is vital in maximising these different sources of value. PPPs initiatives have been a common vehicle in telecoms for public authorities to pursue socio-economic objectives. For example, Wi-Fi deployment, particularly at the municipal level, and the afore-mentioned interventions in high-speed broadband access are good precedents for public intervention in 5G.

There are a number of different ways of structuring PPPs and the European PPP Expertise Centre identifies four approaches [Eup12]:

- Private design build & operate;
- Public design, build & operate;
- Joint venture (public and private); and
- Public sector outsourcing.

The four approaches can be thought of as different mechanisms, each with their advantages and disadvantages, to incentivising private service providers to deploy infrastructure beyond the commercially profitable level so that the full socio-economic benefits are gained. For example:

- Projects done wholly by the public sector will have the strongest incentives for network deployment that maximises the benefits to society, but they may lack the technical expertise and existing infrastructure of the mobile network operators and will not benefit from the economies of scale that the national operators possess;
- The public sector has assets such as sites for small cells which could reduce the cost of network deployment. The public authority could seek to become an InP by acquiring spectrum and building a network itself, however it might be easier to become a tenant on an MSP's network. So both the public and private sector have something that is valuable to the other therefore a joint venture could be an appropriate solution, though it is not the only possible solution.
    - "Bristol is Open" is a publicly run, virtualised wireless infrastructure for R&D purposes, built on an open network platform. It is run by the University of Bristol and Bristol City Council and is a Horizon 2020 project. Interestingly, it is

[15] So it is possible that cities might be higher priorities for government intervention than rural areas, but that will depend on the relative commercial viability of deploying 5G in each area and the impact on social benefits.

drawing in many private sector partners as tenants. Zeetta Networks is a key partner in provisioning the multi-tenant platform [Zet17]. "Bristol is Open" may represent a future model for PPPs providing commercially run services, assuming there was a compelling justification for intervention.

- Public sector outsourcing allows governments to control the scope of network deployment to increase the benefits to society, and brings in private sector expertise. However, governments face a challenge in setting contracts so that contractors are paid fairly while securing value for money for the public. Governments will also have to consider how to avoid distorting competition if they give assistance to individual companies.

#### 5.2.1.3 Stimulating application demand and innovation is also important for sustainable infrastructure

Programmes to promote digital access and inclusion, and next generation broadband deployment have all identified that support for other measures may be necessary if government intervention is to be truly sustainable. Although infrastructure has attracted the majority of funding, other areas have also been allocated funding in several projects. For example:

- The ITU also identified education, telecentres and access points, and locally produced content as priorities for action in its SADC[16] toolkit on Universal Access Funding and Universal Service Fund Implementation, 2011;
- Smart cities programmes such as the USA's Smart Cities Initiative[17] includes government grants to organisations supporting an array of projects in healthcare, transportation, emergency response, and others;
- The project SmartSantander, funded under the EU Future Internet programme, identified the need to engage application developers and service providers, particularly by providing testbeds that could spur innovation as well as new services to create demand; and
- Next generation access projects also funded education, and ICT developers, e.g. the BUL (Banda Ultralarga in Lombardia) FTTH joint venture in Lombardy, Italy had a significant focus in these areas as summarised in [Epe12].

In summary, there appears to be a growing recognition of the importance of stimulating demand directly through end-user education and awareness and indirectly through encouraging the development of local applications and content provision that will attract end-users. The benefits of being open to other stakeholders with testbeds for developers are also increasingly accepted.

The public sector can increase the sustainability of infrastructure developments by being an early adopter itself and an anchor user. This may be particularly relevant for towns and city authorities since smart cities (which may have substantial societal benefits) are seen as important drivers for the use of IoT and MTC.

## 5.3 Assessment of social value of each example service in the central London scenario

In this section, we present our forecasts for social benefits relating to the services we considered in the socio-economic analysis and summarise the methodology behind the calculations.

---

[16] Southern African Development Community

[17] US$160 million funding was announced in September 2016 by the White House

### 5.3.1 Social benefit assumptions for V2I

We identify three potential sources of benefit which apply to the assisted and semi-automated driving market segments (as described in Section 4.2) only. These benefits arise from reducing the negative effects of road traffic on individuals and society, namely reductions in:

- Road traffic accidents due to improved control of vehicles and access to better information on road conditions:
  - This benefit can be measured in terms of the number of accidents avoided [DfT15]; and the costs to society per road traffic accident – UK government data on average cost of road casualties include value lost to society from fatalities, cost of medical care and of lost economic output[18] [Dft16].
- $CO_2$ emissions or equivalent from smoothed out traffic flows, better fuel efficiency and reduced congestion:
  - This benefit can be measured in terms of reduction in tonnes of $CO_2$ produced [Dec15] and the cost of non-traded $CO_2$ emissions [Dft16]. Non-traded $CO_2$ emissions costs are based on the costs of meeting $CO_2$ emissions reduction targets. They are used in preference to traded $CO_2$ emissions costs which represent the cost of buying permits for $CO_2$ emissions in the EU Emissions Trading System carbon trading scheme which are administratively set.
- Reduced journey times due to smoother traffic flows from assisted driving and better information about traffic congestion – the reduction in congestion will also depend on smart city / traffic management systems:
  - This benefit can be measured in terms of the potential time savings and their value to drivers & passengers [Dft16].

The social benefit for each of the negative effects outlined above is calculated as the product of:

The total volume (or incidence) of the negative effect, percentage uptake of V2I, societal value of avoiding the negative effect per unit and percentage reduction in the negative effect due to V2I services.

There is little direct evidence on the impact of assisted driving on these negative road traffic impacts and particularly on the incremental impact of 5G compared to legacy technologies. However, in terms of the impact of all assisted driving technologies (4G, 5G and on-board systems) [Kpm15] assume that there will be a 47% reduction in UK road accidents by 2030.

Clearly the impact of 5G will be a fraction of this. We again created three scenarios to cover the range of outcomes that we thought were reasonable. In our low, middle and high scenarios, we assumed that the percentage impact ascribable to 5G was 2.5%, 5% and 10% respectively of the total value of reduced accidents, for each social benefit. Table 5-2 shows the incremental impact of 5G compared to existing services in reducing these socially harmful effects.

Figure 5-2 presents the social benefits alongside the revenue forecasts for V2X services which provide the wider context. It suggests that social benefits are of a similar order of magnitude to revenues, and may be higher or lower depending on the precise willingness to pay of consumers. The analysis in Chapter 4 suggests the risks to the commercial business case are likely to be higher in cities and towns that are not as densely populated as the Central London area. Hence, from a wider societal perspective, the social benefits from V2I could tip the balance in favour of the faster deployment and more extensive coverage of 5G NORMA networks.

---

[18] These benefits may be partly covered by reduced costs to insurance companies and reduced insurance premium charges. However, insurance policies cover accident related effects to different levels and arguably may not reflect the full value to society of fatalities. Moreover. medical costs may be wholly or partially borne by public authorities.

**Table 5-2: Assisted and automated driving social benefit forecast, Central London, £ million per year**

| | 2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 | 2029 | 2030 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Reduced congestion** | 0.0 | 0.0 | 0.0 | 0.1 | 0.1 | 0.2 | 0.3 | 0.4 | 0.6 | 0.8 | 1.1 |
| **Greenhouse gas emissions** | 0.0 | 0.0 | 0.1 | 0.1 | 0.1 | 0.2 | 0.3 | 0.5 | 0.7 | 1.0 | 1.2 |
| **Reduced road traffic accidents** | 0.1 | 0.2 | 0.3 | 0.5 | 0.7 | 1.2 | 1.8 | 2.8 | 4.0 | 5.3 | 6.8 |
| **Social benefit total: Middle** | **0.1** | **0.2** | **0.4** | **0.6** | **1.0** | **1.6** | **2.5** | **3.7** | **5.3** | **7.2** | **9.1** |
| | | | | | | | | | | | |
| **Social benefit total: Low** | **0.1** | **0.1** | **0.2** | **0.3** | **0.5** | **0.8** | **1.2** | **1.9** | **2.7** | **3.6** | **4.5** |
| **Social benefit total: High** | **0.3** | **0.4** | **0.7** | **1.2** | **2.0** | **3.2** | **4.9** | **7.4** | **10.6** | **14.3** | **18.2** |
| | | | | | | | | | | | |
| **Total revenue: Middle (For comparison)** | **0.4** | **0.7** | **1.1** | **1.8** | **2.8** | **4.2** | **6.1** | **8.5** | **11.4** | **14.4** | **17.4** |

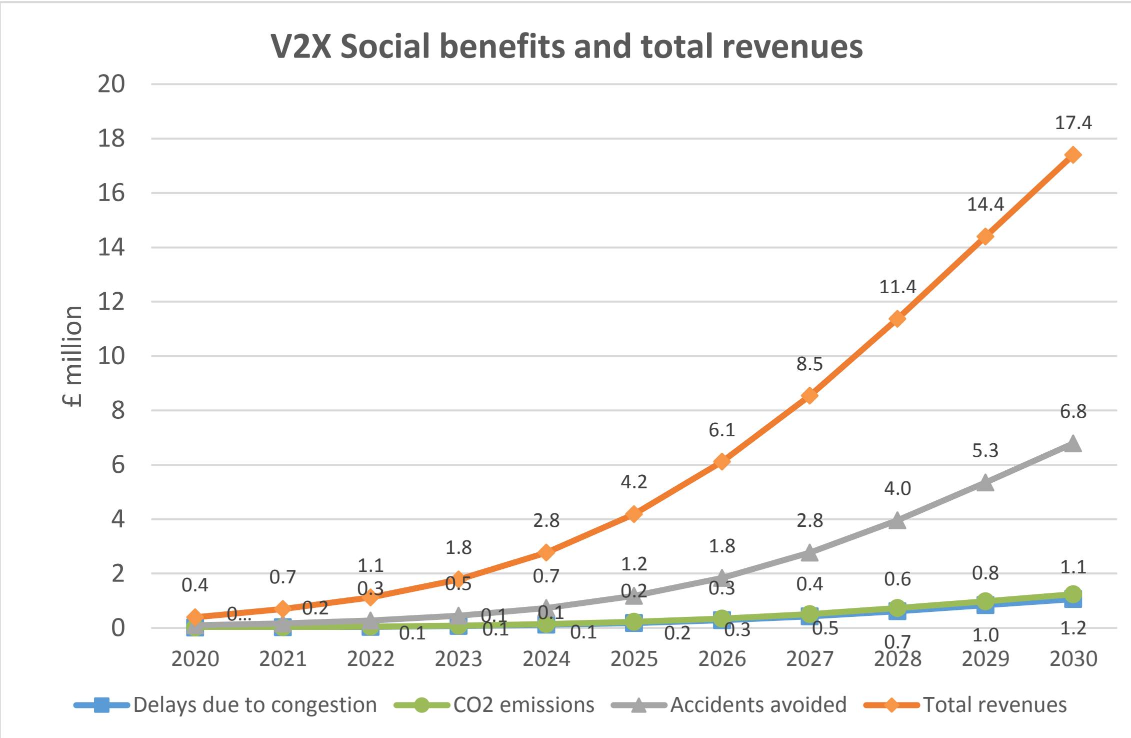



**Figure 5-2: Graph of social benefits and revenues for assisted and automated driving, Central London, £ million**

### 5.3.2 Social benefits from smart city services

Limited information is available for making reliable quantitative forecasts for smart city services. This is partly due to the early state of development of smart city services and partly to the diversity of services which makes it difficult to standardise. As a result, we have focused on the services most amenable to quantification – intelligent transport systems and smart energy.

Although there are benefits to society from water and sewerage systems, these services are largely paid for directly by households and business. The amount that service users pay is enough to enable the market to provide the socially optimal level of these services. Hence, we have not identified any wider benefits to society from smart meters in this industry beyond those that are paid for directly by the "consumers" of these services.

#### 5.3.2.1 Social benefits from smart grids and meters

We focused on the impact of reduced greenhouse gas emissions in assessing the social benefits of smart meters and grids. Other benefits could arise from enabling the elderly to remain in their homes for longer (due to remotely monitored and operated electrical and gas appliances) or reduced care costs for people with some chronic illness. However, we consider that such benefits are more relevant to smart home applications and healthcare, so we do not consider them here.

**Smart meters** – We used estimates from the UK Department for Business, Energy and Industrial Strategy [Dbe16] as the basis for our estimates. This predicted that smart meters could lead to savings of 19 million tonnes of $CO_2$ over the period 2013-30. We assumed that this would be spread out over the period in line with the profile of total smart meter benefits which are predicted to rise at a CAGR of about 3% over 2020-30 [Dbe16]. We multiplied the savings in $CO_2$ emissions by the cost of non-traded $CO_2$ emissions predicted for 2020-30 [Dft16] to calculate the total value of the reduction in emissions – i.e. the potential social benefits from smart meters.

Finally, we assumed 10%, 20% and 40% of the change could be apportioned to 5G for our low, middle and high scenarios.

**Smart grids** – Our approach was to estimate the share of potential reductions in greenhouse gas emissions that could be attributed to smart grids. We hypothesised that, without government intervention on climate change, the status quo would be a continuation of $CO_2$ emissions at the same level from 2020 onwards. With government intervention, the targets set out in the Climate Change Act, reported by the UK Committee on Climate Change [Ccc17] would be reached.

According to estimates produced by EC DG Energy [Dge17][19], smart grids could reduce $CO_2$ emissions by up to 6%. We take this to mean that by 2050, smart grids would be responsible for a 6% fall in emissions and in total $CO_2$ emissions should have fallen by 80%. Hence smart grids would be responsible for 7.5% of the 80% emissions reduction.

Using this figure, we assumed that 7.5% of the difference between the status quo and the $CO_2$ emissions target could be attributed to smart grids each year from 2020-30. This gave an annual benefit in million tonnes of $CO_2$ emissions avoided from using smart grids. We multiplied this by the cost of non-traded $CO_2$ emissions predicted for 2020-30 [Dft16] to calculate the total value of the reduction in emissions – i.e. the potential social benefits from smart grids.

Finally, we assumed 50%, 75% and 90% of the change would be due to 5G in our low, middle and high scenarios.

#### 5.3.2.2 Social benefits from intelligent transport systems

For intelligent transport systems, we based our social benefit estimates on figures from TfL and the “surface intelligent transport system” it has commissioned (as described in Section 4.3.1.1). We assumed that social benefits will arise from two of the stated aims of the new system: reduced travel times (due to better management of or a reduction in congestion) and reduced greenhouse gas emissions (from reduced congestion and better traffic flow management). These social benefits are likely to overlap with those of V2I services.

There is little evidence to estimate the incremental impact of 5G on these social benefits. However, we believe that V2I services will have a larger impact than the intelligent transport system since they directly act on the vehicle. We assume that 5G will lead to a 1%, 2% and 4% reduction respectively in travel time and greenhouse gas emissions in relation to our low, middle and high scenarios. The sources for the value of reducing travel time and emissions per unit are the same as for our V2I analysis.

[19] This suggests that smart meters and grids can reduce greenhouse gas emissions by 9%. A 2:1 splits in favour of smart grids can be inferred from the same site’s figures on energy savings due to smart meters and grids.

#### 5.3.2.3 Summary of social benefit forecasts

Table 5-3 presents our forecasts for the impact of 5G on social benefits arising from smart city services. The social benefits are dominated by the savings from smart energy, particularly smart grids. We can also see that the latter significantly outweigh the total direct revenues we forecast for smart city services which were presented in Chapter 4. This suggests that there may be a role for government intervention in order to secure these substantial social benefits. Governments should consider carefully the risks that commercial networks might not provide sufficiently extensive 5G coverage, as identified in Chapter 4, and incorporate these considerations into their strategy for managing the transition to a low carbon economy.

**Table 5-3: Smart city social benefit forecast, Central London, £ million per year**

| | 2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 | 2029 | 2030 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Smart meters: $CO_2$ emissions saving** | 19 | 21 | 23 | 23 | 25 | 26 | 27 | 28 | 28 | 29 | 30 |
| **Smart grids: $CO_2$ emissions saving** | 40 | 101 | 205 | 312 | 423 | 537 | 596 | 657 | 719 | 783 | 848 |
| **ITS: $CO_2$ emissions saving** | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 |
| **ITS: reduced congestion** | 0.6 | 0.6 | 0.6 | 0.6 | 0.6 | 0.6 | 0.6 | 0.6 | 0.7 | 0.7 | 0.7 |
| **Social benefit total: Middle** | **60** | **123** | **229** | **337** | **449** | **564** | **625** | **686** | **749** | **813** | **880** |
| | | | | | | | | | | | |
| **Social benefit total: Low** | **36** | **78** | **149** | **221** | **295** | **372** | **412** | **453** | **494** | **537** | **581** |
| **Social benefit total: High** | **88** | **165** | **294** | **424** | **560** | **699** | **773** | **847** | **922** | **1,000** | **1,081** |
| | | | | | | | | | | | |
| **Total revenue: Middle (For comparison)** | **1.4** | **1.6** | **1.7** | **1.8** | **2.0** | **2.2** | **2.5** | **2.7** | **3.0** | **3.2** | **3.4** |

### 5.3.3 Social benefits from logistics

Social benefits from the use of mMTC in logistics arise from the increase in vehicle loading it facilitates. This leads to a reduction in road haulage km (everything else being equal) resulting in a concomitant reduction in greenhouse gas emissions.

The social benefit equals the total $CO_2$ equivalent emissions from road haulage multiplied with the incremental impact of 5G NORMA on vehicle loading, the value to society per tonne of greenhouse gas emission saved ($CO_2$ equivalent) and the take up of mMTC logistics service. The sources for these assumptions are:

- Total UK $CO_2$ equivalent emissions from road haulage are given by the UK National Statistics [Ons14];
- The maximum potential efficiency saving is 26% following the [Ec15] methodology, as in the revenue calculations. We assume low, middle and high scenarios for the 5G impact as 1.5%, 2% and 2.5% of the maximum (in value terms) respectively basing the middle scenario on [Ec15] and flexing the others around it;
- The value of $CO_2$ equivalent emissions comes from [Dft16] as in the relevant social benefit calculations for V2X and smart energy; and
- We project the take up of the mMTC logistics services using a saturation curve methodology similar to that used in forecasts for other services. We assume a reasonably fast uptake reaching 82% penetration of vehicles by 2030.

#### 5.3.3.1 Summary of social benefit forecasts

Table 5-4 presents our forecasts for the impact of 5G on social benefits from logistics in the form of reductions in greenhouse gases. These social benefits are an order of magnitude less than the direct revenues we forecast for logistics and the social benefits identified for smart energy. This is partly due to the fact that we have been conservative in estimating social benefits from logistics in order to avoid double counting with the social benefits from V2I and intelligent transport systems.

**Table 5-4: Logistics social benefit forecast, Central London, £ million per year**

| Greenhouse gas reduction | 2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 | 2029 | 2030 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Social benefit: Middle | 0.00[20] | 0.00 | 0.01 | 0.01 | 0.02 | 0.02 | 0.03 | 0.05 | 0.06 | 0.07 | 0.08 |
| Social benefit: Low | 0.00 | 0.01 | 0.01 | 0.01 | 0.02 | 0.03 | 0.04 | 0.06 | 0.08 | 0.09 | 0.10 |
| Social benefit: High | 0.00 | 0.01 | 0.01 | 0.02 | 0.03 | 0.04 | 0.06 | 0.08 | 0.10 | 0.11 | 0.13 |
| | | | | | | | | | | | |
| Total revenue: Middle (For comparison) | 0.34 | 0.54 | 0.87 | 1.36 | 2.09 | 3.08 | 4.32 | 5.72 | 7.12 | 8.37 | 9.36 |

## 5.4 Assessment of potential impact on productivity

As noted above, we also expect that the 5G NORMA platform will bring longer term dynamic benefits, in particular enhanced business productivity. There is a substantial body of economic analysis which shows that improvements in communications technology brings about measurable improvements in Gross Domestic Product (GDP) growth across a range of developing and advanced economies. Effects have been found for both mobile and fixed broadband, although the majority of the research has centred around fixed broadband.

We can identify two sources of productivity impacts. The first comes from the use of mobile broadband services to improve business processes, e.g. better collaboration and coordination while out of the office. The second relates to productivity improvements driven by the use of MTC communications and IoT (as distinct from eMBB services) in industry which form part of a wider change in business organisation which is sometimes seen as a new industrial revolution and termed Industry 4.0.

#### 5.4.1.1 Impact of broadband improvements on productivity

[GHK14] provide an excellent summary of research that has taken place. Often this involves assessing the impact of either the introduction of advances in telecoms technology, such as fixed broadband, or an increase in service speed, e.g. a jump to Next Generation Access broadband. Most studies take a cross-sectional regression analysis across a number of countries and over multiple years to analyse the relationship between output and broadband or mobile usage. Clearly, service penetration is also likely to be rising over time and most studies separate rising penetration from the impact of increases in average speed, where relevant.

We estimate the impact of 5G on productivity using academic research on the impacts of changes in average user throughput on productivity. Rohman and Bohlin [RB12] have been used in a number of economic assessments, for example by SQW for the Scottish Government, [Sqw14], and we follow a similar approach here.

Rohman and Bohlin [RB12] found that a doubling of fixed broadband speed leads to a 0.3% increase in annual GDP[21] growth averaged over the period of their analysis. Their regression model takes into account potential correlation between GDP and broadband service use: i.e. while

[20] Note in early years the take up of wireless tracking logistics is low and hence the social benefits are small in these years and appear as zero at the resolution shown on this table.

[21] Note, productivity impacts are sometimes measured by the impact on Gross Value added (GVA). GVA and GDP both measure the output of goods and services in a defined area. GDP is used at the national level and GVA is used when considering a sub-section of the national economy, i.e. a specific region, city or industry.

the main assumption is that faster broadband leads to faster GDP growth, there is also a feedback loop in that higher levels of GDP (or income) may increase the take up of higher speed broadband.

We assume that the relative impact of mobile broadband compared to fixed broadband should be related to business revenues (for mobile and fixed telecoms) in order to translate Rohman and Bohlin's analysis to mobile broadband[22]. Hence, we take the value of total mobile retail revenue compared to fixed retail revenues for business (including line rental). In the UK in 2015, this was £3.3 billion for mobile compared with £3.2 billion for fixed broadband according to [Ofc16b].

Other econometric studies have found that the impact of broadband on productivity diminishes at higher levels of broadband speed [JH10] as shown in Figure 5-3. Hence, we assume that the increase will tend asymptotically to a value of 0.6%, i.e. twice the 0.3% estimated in [RB12]. This leads to the following curve.

Opinion in the sector varies as to the extent of the performance improvement that 5G will bring compared to LTE-A Pro for 5G mobile services, therefore we have produced three scenarios to cover the range of plausible opinion on this issue.

Table 5-5 shows the increase in GDP due to the impact of increased eMBB performance on productivity for 2020 and the Net Present Value (NPV) of the GDP uplift from 2020 to 2030 (using the UK government's social discount rate of 3.5%) [Hmt13][23].

We tie the uplift in GDP to the penetration of eMBB in the business market segment. We also take into account the increase in the 5G performance that results from the potential increase in 5G spectrum availability that we expect to take place in 2025.

Therefore, we should be able to project indicative values by applying the following logic. GDP would increase by £3.66 billion in 2020 in our middle scenario if eMBB penetration were 100% in the business market segment, compared to a £274 million increase in GDP given our 2020 penetration forecast of 7%. As shown in Table 5-6, over 2020 to 2030 our estimate of the total impact on GDP is £20.4 billion in present value terms using the social discount rate of 3.5% as recommended by the UK Treasury.

[22] [SQW2014] uses the time spent using fixed and mobile broadband to compare the relative impact, however we feel that the business spending is more appropriate.

[23] The Green Book: appraisal and evaluation in central government, UK Treasury, 2013, https://www.gov.uk/government/publications/the-green-book-appraisal-and-evaluation-in-central-governent

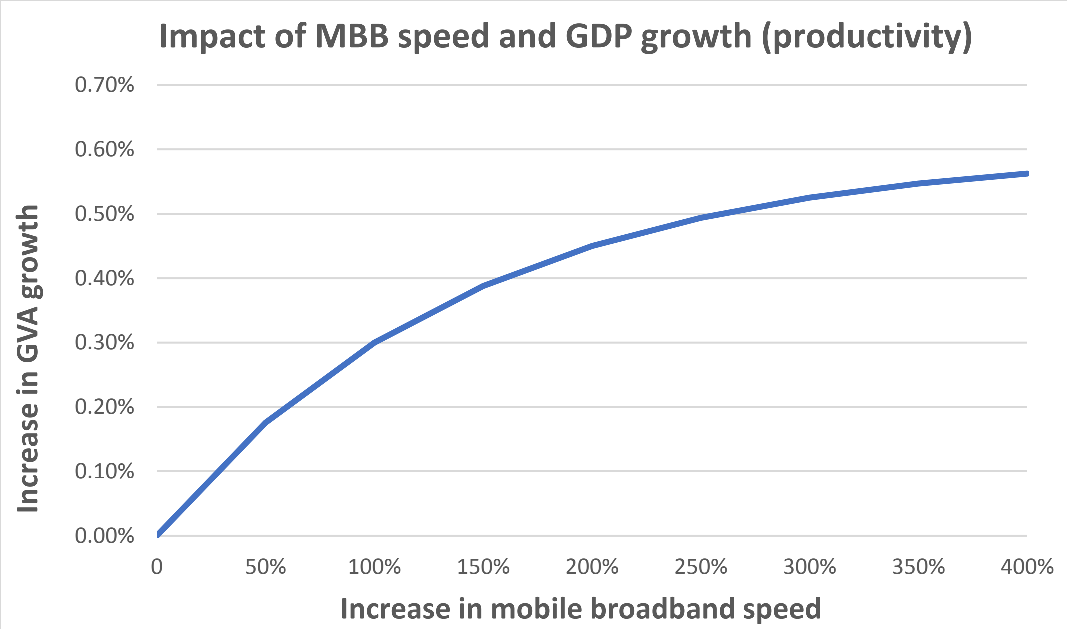



**Figure 5-3: Estimated relationship between changes in average mobile user throughput and GDP**

**Table 5-5: Annual impact of eMBB on productivity and GDP for UK (2020 base year, 100% eMBB penetration in the business sector)**

| | Low | Middle | High |
|---|---|---|---|
| **Increase in MBB speed** | 10% | 50% | 100% |
| **Impact on productivity** | 0.04% | 0.18% | 0.30% |
| **Annual impact on GDP (£m)** | 837 | 3,661 | 6,250 |

**Table 5-6: Annual impact of eMBB on productivity and GDP for UK (adjusted for uptake of eMBB in the business sector)**

| | 2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 | 2029 | 2030 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Annual impact on GDP: low** | 63 | 133 | 224 | 327 | 416 | 509 | 608 | 722 | 857 | 1,000 | 1,020 |
| **Annual impact on GDP: middle** | 274 | 584 | 980 | 1,429 | 1,819 | 2,224 | 2,658 | 3,158 | 3,747 | 4,376 | 4,463 |
| **Annual impact on GDP: high** | 468 | 996 | 1,673 | 2,440 | 3,106 | 3,797 | 4,538 | 5,391 | 6,397 | 7,470 | 7,620 |

#### 5.4.1.2 Impact of Industry 4.0 on productivity

While we can use the historical impact of changes in fixed and mobile broadband services on productivity as proxies for the impact of eMBB services, there is no historical analogue for the impact of MTC/IoT services on productivity.

A number of organisations have strongly suggested that Industry 4.0 could have a significant impact on productivity in manufacturing, for example [Ep15]. However, these estimates of the potential impact on productivity are based on hypotheses about the level of efficiency benefits possible with Industry 4.0 rather than observed productivity effects.

According to Boston Consulting Group [Bcg15], Industry 4.0 comprises:

- Big data and analytics;
- Autonomous robots;
- Enhanced simulation techniques;

- Horizontal and vertical systems integration;
- Cyber security;
- “The cloud”, i.e. cloud based software and data sharing;
- Additive manufacturing, i.e. small run, highly complex, decentralised production at low cost using technologies such as 3D-printing;
- Augmented reality;
- The industrial internet of things.

As this illustrates, Industry 4.0 is made up of a number of IT and communications technologies. This is important to note because the impact of communications will only be responsible for a part of the total productivity impact of Industry 4.0. Moreover, the impact of 5G in this area will only be a fraction of the total communications impact because to some developing 4G technology such as LTE-M would meet at least some of the needs of Industry 4.0.

[Bcg15] estimate that the Industry 4.0 could lead to productivity growth of 5-8% in manufacturing in Germany, generating €30 billion in revenue. This is equivalent to roughly 1% annual increase in GDP. However, it is difficult to allocate this productivity change to 5G since we have not looked in depth at the implications of the 5G NORMA architecture for Industry 4.0.

## 5.5 Conclusions on action needed to realise social value of 5G NORMA

The EU’s 5G Action Plan under its Digital Single Market programme and other areas of government involvement in telecoms show that government intervention to secure the wider socio-economic benefits that 5G may generate can be objectively justified in the current economic and regulatory framework in the EU.

The key issue for determining whether government intervention is needed in this case are the extent of the social benefits and whether it will be commercially viable to provide these services to the degree necessary to maximise the social benefits.

Our research suggests that the social and wider economic benefits are substantial. The greatest benefits are likely to come from smart energy, V2I services and increases in productivity related to eMBB and services specific to the verticals, including those falling under Industry 4.0 and others (but not covered in detail in this study). They are of similar orders of magnitude to the revenue forecasts presented in Chapter 4 and in some cases, e.g. smart energy, they are substantially higher.

There are several indications as to where intervention may be appropriate, although further research will be necessary, particularly for lower population density areas, to refine this initial research:

- There is a question mark over whether eMBB will continue to be sufficient to cover the cost of infrastructure by itself although the commercial business case is improved by the economies of scope from deploying multi-service networks as shown in Chapter 4.
- Although the data volumes involved in smart energy are small compared to other services such as eMBB, it will need nation-wide, reliable coverage. Our business case assessment in Chapter 4 suggested that there could be material risks to the business case in areas less densely populated than Central London, therefore there is a risk that the market might not be able to provide the necessary coverage on a nation-wide basis. Much depends on how the energy market itself develops and whether microgeneration and electric vehicle charging take off and require dense sensor and actuator networks. We recommend that analysis of the risks to adequate smart grid provision should be incorporated into the strategy for the energy sector and the transition to a low carbon economy.
- V2I services are likely to be commercially viable particularly in the most densely populated cities. However, it is not clear whether the same would be true of the road

network outside these areas, particularly given that the quality of mobile coverage on these roads can already vary significantly.

There are a number of different models for intervention, particularly those involving public private partnerships. The key lessons to learn from past interventions is that they should be targeted (in time and in scope) and sustainable, i.e. intervention should not only cover infrastructure, but also applications where there is arguably more potential for value creation.

# 6 Implications of the disrupted business environment with 5G NORMA

The majority of the analysis in this report focusses on the viability of the potential innovations of 5G NORMA. These innovations are focused on the technology transformation of the network. However, through the logical approach of the analysis from use cases, stakeholder identification, through to expected revenues and traffic and associated costs, the discovery of threats and opportunities for the telecommunications industry and adjacent or vertical industries are apparent. These threats and opportunities establish the context not only for the transformation of the network but of the industry. This section predominantly explores the business models that the MNOs may follow as a result of incremental innovation but also through disruption, with a focus on MNO driven use cases. Other players are also considered as the mobile landscape evolves in response to 5G. It examines the potential impact on revenue (in a qualitative sense) for MNOs in relation to these business models including the opportunities to target a wider proportion of the value chain than mobile infrastructure and connectivity services.

Figure 6-1 illustrates a potential 5G value chain of the future. It sets out the different types of services which can be distinguished in the provision of a service though not all the elements are necessarily present in each implementation of the overall product to the end-user. Traditional MNOs would comfortably inhabit the bottom two layers of this value chain, infrastructure and wireless connectivity provision. Moreover, some are already strong in the middle layer, systems integration. We expect the content and application platform to be the area which has the greatest potential for expansion in 5G. It offers significant potential for the MNOs; but competition is likely to be strong from both OTTs such as Google and the vehicle manufacturers, and from smaller companies with specific vertical industry skills and relationships. Sometimes, equipment vendors (hardware and software) are added to telecoms value chains, below the infrastructure level, but although they play an important role in the industry, we have chosen to focus on service provision in this case.

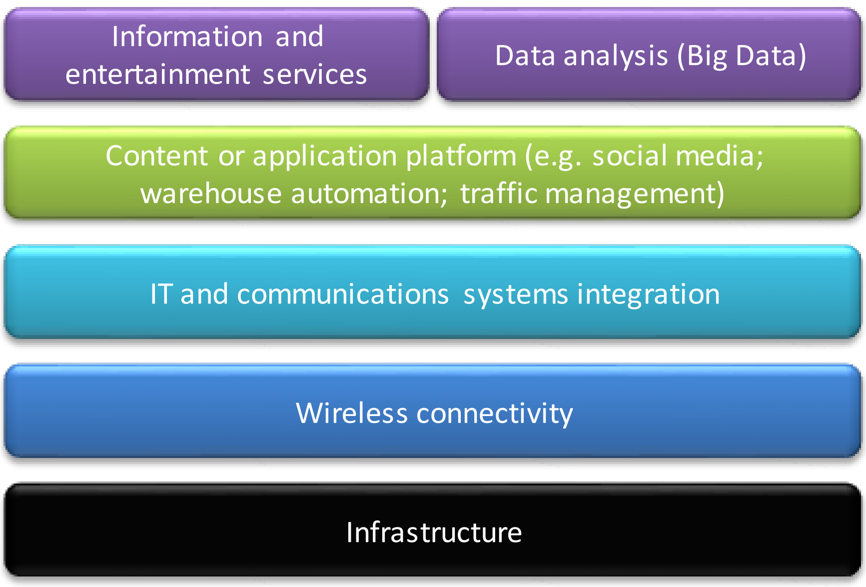



**Figure 6-1: Mobile sector value chain [Source: Real Wireless]**

In 5G NORMA [5GN-D32], we have established stakeholder roles that will emerge in 5G, the relationships between the new stakeholders and the transition from today's stakeholders. These are illustrated in Section 1.4. We note that the stakeholder analysis has been driven from a technical perspective and to assess the technical feasibility of the new stakeholder roles. There are clear connections with the value chain, but the stakeholder roles do not necessarily capture fully the different sources of value generation and the opportunities for companies in the mobile sector to move up the value chain.

Our analysis of new business models is part of a wider analysis of the potential social and economic impact of the innovative architecture developed in the 5G NORMA project. This analysis has so far focused on the potential cost savings from the 5G NORMA innovations, the arguably limited potential for increasing revenue as a result of the performance improvements brought by the 5G NORMA innovations and the potential wider social benefits.

This type of incremental cost and revenue analysis is good at estimating the direct benefits from improved performance of the 5G NORMA architecture, but it is not so good at capturing the potential for change – increased dynamism and diversity in end-user applications that 5G NORMA innovations could bring. In the wider analysis, Evaluation Case 3 looks at the benefits of the 5G NORMA architecture's multi-service innovation (in particular, potential cost savings and revenues from a limited range of easily identifiable services). We take a wider look at the potential for service innovation (in particular moving up the value chain) and the opportunities for MNOs as IoT and MTC services develop and change. If these additional benefits are significant, they could be important in making the 5G investment case more viable for operators, given that the investment case is unlikely to be viable based solely on the direct increase in revenues due to 5G when compared to today's 4G networks.

The business models are important because the key network providers in the 5G supply chain (whom we name InPs and MSPs) will have a significantly enhanced ability to tailor network performance to the needs of end-users and will be able to open up their network to multiple tenants (or 3rd party service providers). This expands the range of possible relationships between infrastructure operators, mobile service providers, application and systems designers, and consumers. It also provides a framing for strategic activities such as strategic alliances and eco-system building.

The new 5G business model(s) we examine can be thought of as a way for today's MNOs to navigate their way through the altered relationships in the evolving supply chain. The choice of business model will affect the opportunities open to other players as well as the traditional MNOs. It will also, we contend, affect the development of the market as a whole which will feed back into mobile connectivity revenues (i.e. for InPs and MSPs in the 5G supply chain). Because of this feedback loop, the impacts on the players are harder to quantify. Hence, we give indications of the likely implications for today's MNOs, their competitors and potential partners, rather than explicit forecasts.

**Approach**

Our approach has been to examine some of the leading business models currently emerging in the context of MTC and IoT over 4G and proprietary networks. We focus specifically on mobile connectivity providers (i.e. networks and mobile communications services) and explore their business models and partnership strategies with other players in the supply chain.

Crucially, we then identify those business models that may be enabled or enhanced by the key 5G NORMA innovations in order to draw out the relevance for the economic assessment of the 5G NORMA in this context. This analysis of operator business strategies in 5G and the opportunities that may be open to operators to move up the value chain provides a useful context for analysis of viability of innovations.

## 6.1 MNO driven use cases

The business model canvas (BMC) [Ost13] provides a useful shorthand representation of the principal elements of a business model. The standard business model for a MNO today is as shown in Figure 6-2.

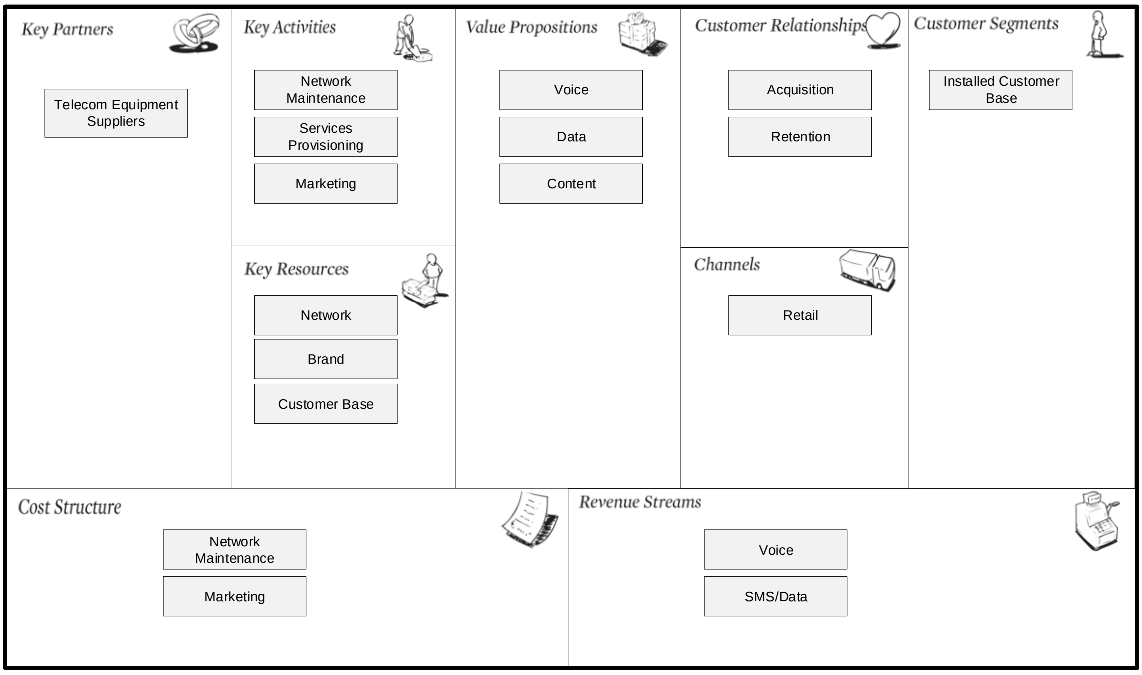



**Figure 6-2: Standard business model for a MNO today as represented on the business model canvas**

The implications of the creation of the new stakeholder of MSP (Figure 6-3) is a reduction in the cost base due to reduced ownership of infrastructure. However, there will be costs towards key partners (infrastructure providers) in terms of infrastructure usage and the key resource of virtual network requires a software based framework for handling/managing virtualized networks that run across the used infrastructure. The customer segment also changes to focus on B2B oriented sales channels to acquire tenant customers. The figure illustrates the elements that are left behind (light grey text) and new element emerge (orange box).

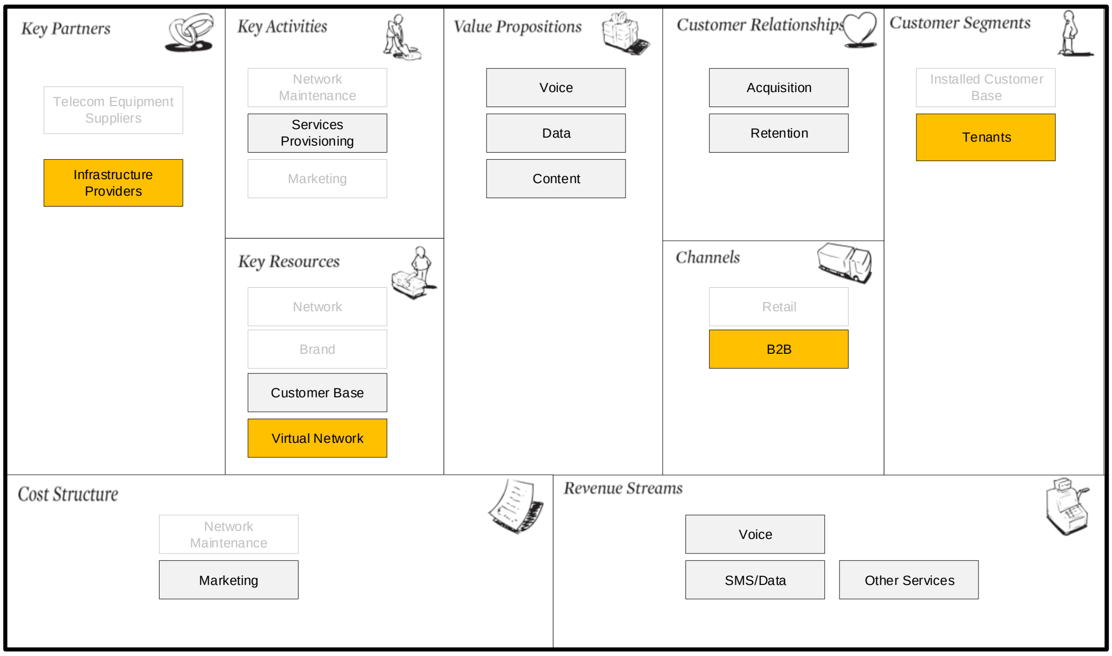



**Figure 6-3: MSP Business Model**

Key activities can orient towards the provisioning of services based on orchestrating of virtualised resource to address the tenant and the tenant's customers' needs. In 5G NORMA Orchestration enables service provisioning and thus emerges as a significant functional element in the future network. This provides the opportunity for the development of independent generalized orchestration services (Orchestration-as-a-Service), or orchestration services that are specialized towards particular verticals. The critical outcome of the orchestration process is the right-size dimensioning of the slices with appropriate allocation of compute, storage, and networking resource and perhaps in some instantiations spectrum as well. Analysis of approaches to pricing of slices in 5G NORMA yielded significant outcomes as described in the next subsection.

In the following sub-sections, we establish through the example of an IoT case study the potential of the inter-slice resource broker. This functionality has also been explored in a wider service (MBB, uMTC) context and thus can address more general business segments that are explored in subsequent sub-sections.

To illustrate the change that is already underway in the telecoms industry, and thus validate claims around the willingness to invest and establish MNO driven use cases we then provide brief case studies. Some leading public examples of how MNOs (and other mobile connectivity providers) are already entering into partnerships or executing corporate venturing activities with others in the wider MTC/IoT supply chain. The objective of 5G NORMA is to provide network enabling levers to support and accelerate the transformation, thus we assess likely relevance when exploiting the opportunities in these new markets as the industry moves beyond today’s 4G services and towards 5G.

### 6.1.1 5G Network Slice Broker as a business mediator

Although the flexibility expected with network slicing dynamics pushes for a network virtualisation evolution, the infrastructure providers do not really quantify the real benefit brought to their current business cases. There is a need of assessing and brokering the network slicing operations between infrastructure providers and different tenants. In the context of 5G NORMA architecture, we have designed and analysed a new logically centralized entity, namely 5G Network Slice Broker [SCS16] that resides into the infrastructure provider’s network in charge of admission control operations while evaluating network slice requests coming from tenants.

This functional block provides a practical means to optimally allocate and configure RAN slices based on on-demand network slice requests, and will be further extended to provisioning end-to-end network slices. This is envisioned as an added value for the network operators --efficiently responding to the network paradigm change-- which might provide network slicing capabilities as a service, dubbed Slice as a Service (SlaaS), while pursuing revenues maximization [BGB+17].

#### 6.1.1.1 The “Internet of Things” segment

The pivotal benefit with a multi-tenant-enabled network is the ability for industrial segments to acquire and “share” the same network infrastructure to provide own services to their own customers. The Internet of Things segment is considered as the most suitable customer exploiting a self-managed and isolated slice of network resources, given the high heterogeneity level of its traffic requirements. The advantages of engaging IoT use cases are the following:

- IoT traffic is flexible enough to be reshaped based on the service demands/network conditions;
- IoT traffic may require advanced Service Level Agreements (SLAs) for very short periods directly resulting into additional profitable gains for the infrastructure providers.

We can consider an IoT system built as part of a 5G network slice, wherein sensors communicate wirelessly (via e.g. Bluetooth, ZigBee, LoRa technologies) with an IoT Gateway (GW), which is capable of handling, storing and exposing data through 5G facilities. The IoT platform, then, enables the communications between IoT devices and applications in a service-oriented fashion. The IoT traffic flows transmitted can be optimized based on advanced inter-slice policies for resource allocation in order to reduce the capacity burden on the 5G network slices [PPF+17]. In the cloud environment, an IoT Broker is in charge of interacting with external applications while optimally delivering different data information via resource policies. In addition, the Broker influences IoT traffic shape by application of service-aware QoS at the application level. The ability to optimise sliced network capacity enables resource efficiency in the network.

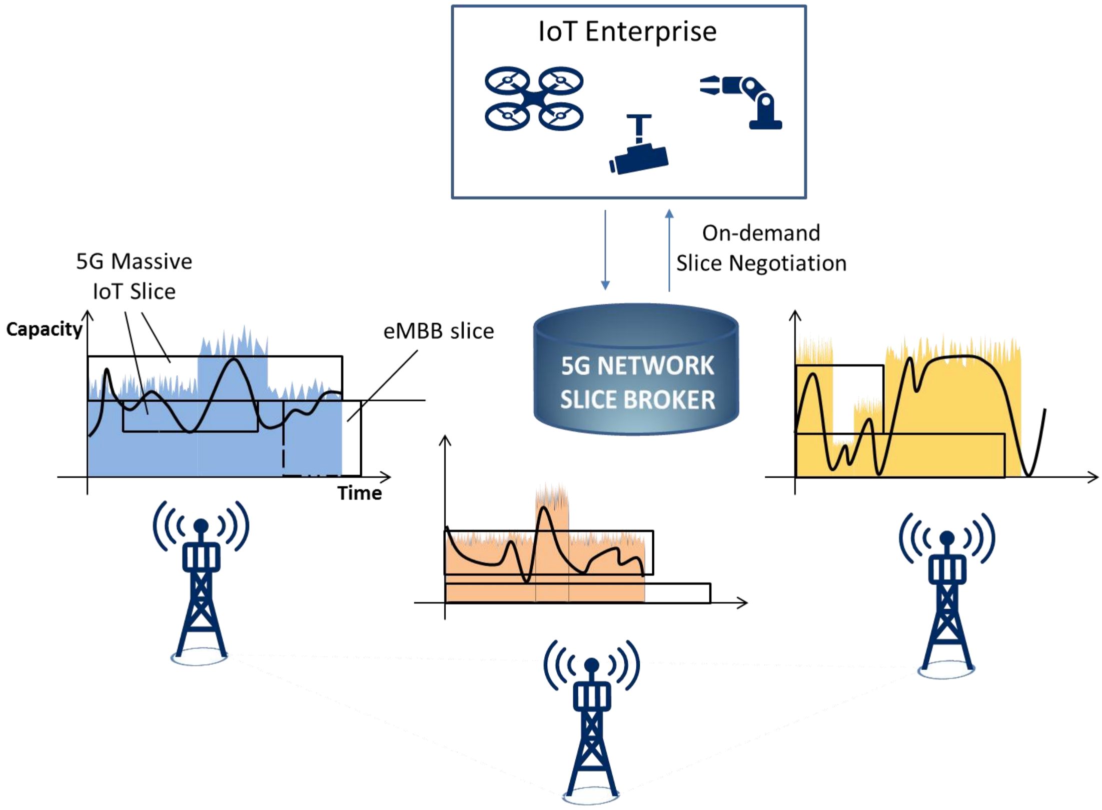



**Figure 6-4: 5G Network Slice Broker in action: an IoT slice negotiation.**

When blending together the IoT traffic reshaping features with a 5G NORMA network management, the infrastructure provider can readily pursue network utilization maximization and QoS satisfaction, as shown in Figure 6-4. The idea is to solve the provider-customer problem for efficiently allocating, maintaining or configuring the 5G network slice for IoT devices while fulfilling the communication constraints between IoT players (i.e., IoT GWs and IoT Applications). Therefore, the 5G network slice broker may act as a business mediator between the IoT platform and the 5G network management responsible for properly configuring network slices and can automatically perform the following operations (not limited to):

- limiting (e.g., by changing granularity, quality and frequency of IoT requested information) the IoT messages load when network congestions occur;
- rescheduling IoT messages for under-loaded periods of time (to increase the overall system efficiency);
- preparing network facilities (e.g., by rescaling other network slices, offloading, denying) when mission-critical messages must be exchanged between IoT players in safety contexts.

## 6.1.2 Automotive Sector

### 6.1.2.1 Telefonica – fleet management for car rental companies

Telefonica's car rental telematics service was launched in 2014. Telefonica had its own telematics platform, but in November 2014 it announced a partnership with telematics company Geotab to address the fleet management market.

However, the partnership is presented as an integration of Geotab into Telefonica's telematics system (and only for a specified set of countries). Hence, Telefonica appears to be very much the leading company in the partnership and seems intent on owning the customer. See the case study in [Gsm16]. Furthermore, Telefonica mentions a support network of specialist partners that enables it to serve customers across its international footprint e.g. for the in-car hardware and telematics applications. This shows eco-system building at work in this vertical around the Telefonica developed platform. The service provides real time fleet management services aimed at increasing efficiency and optimising vehicle utilisation e.g. collecting information to know when vehicles need a retune vs. a quick turn-around to be re-rented. Also, the optimum time when to sell the vehicle can be determined from the sensor information.

Although the telematics applications may be tailored to each car rental company and their enterprise systems, the car rental company is unlikely to be interested in the fine details of the network connectivity provision but the relationship with the specialist partners providing hardware into vehicles establishes an MSP like model for Telefonica in the automotive vertical, with elements of tenant oriented thinking based on retail customer ownership. Relevance to 5G NORMA innovations can be forecast to emerge through provision of complementary services and ultimately advanced V2X based services. Clearly elements can readily be served by 4G with NB-IoT, the 5G NORMA platform would arguably improve the speed of roll out of new services such as this.

#### 6.1.2.2 DT and the logistics sector

Through T-Systems, Deutsche Telekom has invested in / partnered with companies that provide hardware and innovative cloud based platforms that target specific B2B sectors. For example, Roambee Corporation provides an innovative shipment monitoring service and leverages IoT in the field of logistics [TS17]. Integration into standard enterprise systems for ordering, invoicing etc. may be increasingly important too. The large SAP providers should also be seen as potential competitors (or partners) in the space.

Of course, there are a large number of companies developing in this market segment and it is not clear whether it is advisable for MNOs to follow this kind of strategy which could be classed as trying to pick winners. If the applications continue to require innovation and evolve quickly in the IoT space, risks may be higher. But as long as MNOs don't discriminate against other providers – in providing connectivity services – and investments are relatively limited in value, the downside maybe small and makes more sense when the MNO has a strong IT services / systems subsidiary.

Assuming network functions become virtualised according to the 5G NORMA architecture, opportunities emerge to benefit from synergies for MNOs (and economies of scale in terms of providing the server network and cloud based processing) in designing and managing cloud based functions. There is the risk that cloud based platforms will be so diverse that the MNO or large IT services provider will be continually challenged by new innovators, it is critical that the cloud platform scales dynamically with appropriate control points in the architecture so the MNO retains sufficient control.

DT provides the communications services but also gets a revenue share from the application services platform. Roambee is a specialist supplier in the logistics sector, but also looking to apply services more generally. Many companies are doing similar things to Roambee in the logistics space. The interesting part is that they are looking to provide the IT systems as a service through cloud based platforms, hence reducing the need for upfront investment by the end-user.

#### 6.1.2.3 Vodafone – Connected Cars Telematics

In 2014 Vodafone bought the telematics provider Cobra Automotive. The acquisition intent was to expand the machine to machine business area beyond connectivity and into providing services on top of connectivity. Cobra Automotive was a specialist in telematics software that gathers and reports data from computer-controlled car systems such as steering and brakes. Here Vodafone establishes an automotive B2B platform addressing one of the important connected car platform areas. In the 5G NORMA construct we cast this example as an MSP, and thus we can easily imagine an extension of this business model through a change in the addressed customer segment to onboard tenants that may come from various vehicle OEMs that provide service contracts along with their products.

Today, users such as car makers may be firmly rooted in the mindset of regarding the MNO as a provider of pure connectivity and purchasing SIM cards to fulfil their needs. However, improvements in mobile performance will open up new possibilities for end-user applications. In addition, 5G NORMA's fast service creation capability should spur innovation. As a result, the future opportunities for MSPs could be much wider than for MNOs today.

#### 6.1.2.4 Verizon – acquisition of telematics skills rather than partnership

Verizon's purchase of Hughes Telematics Inc. (HTI) is an example of an acquisition strategy to gain market share in leading the sector of systems and applications development specific to IoT as HTI is a leader in implementing the next generation of connected services for vehicles, including infotainment and fleet based services as well as products and services for mHealth providers and users. This is a direct alternative to the partnership model but both can be pursued concurrently.

Clearly, the 5G NORMA innovations do not necessary enhance this type of 'take-over instead of organic growth' strategy. As an aside, we note that 5G NORMA should have an impact on the systems and applications development area per se.

### 6.1.3 Utilities Sector

#### 6.1.3.1 Vodafone – partnership with water industry specialist

Vodafone is partnering with Toshiba to provide services for Kurita, a global water treatment provider for remote monitoring and measurement. Kurita is a company providing specific services to the water and waste management vertical. Kurita could have self-provided, but global reach was probably an issue. Note that Toshiba has its own IoT application design business. Vodafone's global reach and its other partnerships with hundreds of smaller IoT specialists was also an advantage.

This may set up the possibility of a move away from per unit data volume pricing towards more value based pricing in selling a more end-to-end based service. This may be more easily supported if a network has the 5G NORMA flexibility and adaptable performance management features. In other words, pricing by volume (either per unit or by monthly data limits) is relatively risk averse, but with a more flexible network able to manage highly diverse traffic needs, pricing strategies can become more flexible as well.

### 6.1.4 The costs and approaches to addressing new markets

MNO clients or partners who are focused on specific sectors will have a better understanding of the overall value of the business innovation/service to the end-user. Therefore, being open to a wide-range of B2B partnerships and contracts may also enable MNOs to extract more value for their services. However, this probably requires an expansion and investment in the more customer focused approach previously employed only for large enterprises, to smaller customers and the extra sales costs this implies compared to selling bits and bytes. However, since B2B is important here, the return for MNOs will be multiplied by the success of its B2B clients. The efficient onboarding of tenants could create competitive advantage in future evolutions of the business.

Some MNOs are keenly pursuing revenue-share models, whereby the vendor provides the hardware and software, the mobile operator bills users for the service, and the total revenue from services is shared between the partners. For example, Turkcell has over 33 such partnerships in place, and it relies on its partners for an in-depth understanding of the market.

In additional to targeting consumers directly, mobile operators can partner with distributors who then resell the services. Most major MNOs in the UK for example partner with Wireless Logic, who deliver a range of value-added MTC managed services including CLAAS, a telemetry based connected agriculture system. This is particularly important for clients for whom getting the best network performance is essential e.g. because of coverage (e.g. low populated areas or deeply buried sensors) and the need for long battery lives.

## 6.2 Vertical driven use cases – a precursor to disruption?

The previous section illustrates where through various corporate venturing and strategic alliance approaches MNOs have executed change in their business showing readiness to address verticals. In short, we can refer to these are MNO driven. MNO driven is the dominant analysis perspective of this report and in fact of the overall 5G NORMA business case context. However, the challenge remains for the MNO retention of control of the connectivity and above layer platforms; enabling sufficiently constrained innovation so that they can realise value higher up the value chain. Nevertheless, other players that have scale and own significant components of the platforms can also build out capabilities that leverage connectivity and take ownership of the Tenant-MSP-InP value chain. These may be disruptive to the MNO driven evolution and should at least be bought to the readers' attention.

### 6.2.1 Daimler – fleet management

A good example of the potential for increased competition in 5G comes from Daimler, recognised as one of the leaders in connected cars. Daimler announced a partnership with Volvo owned WirelessCar, an international telematics provider. The initial target is the same fleet management services / car rental market that Telefonica is targeting. This is discussed in [Cbr15]. WirelessCar also has a number of APIs that link information into companies' Enterprise Resource Planning (ERP) processes and software, which makes its services more tailored to the specifics of the fleet management companies.

Significantly, Daimler and WirelessCar are aiming to provide wireless connectivity over whatever networks are out there and may dynamically choose between several service providers and different wireless technologies according to which provides the best signal. This can be especially important in areas of high cellular congestion and rural areas where coverage may be weak.

In the context of 5G, although these companies might naturally adopt the tenant stakeholder role, it is possible they may attempt to be MSPs, particularly if there is a gap in provision or coverage from the established providers or if an MSP offers a slice which allows the tenant no control over configuration and control options. 5G NORMA D3.3 describes three offer types varying in the level of control available for tenants. If MSPs make available 'Offer type 2 - Limited control over slice configuration and control' (in the terminology of 5G NORMA D3.3) or 'Offer Type 3 - Extended to full control …' tenants are likely to have much less incentive to go it alone.

Tenants choosing to become MSPs would be subject to such companies being able to get spectrum. Some telematics companies could even consider deploying their own infrastructure in unlicensed or shared spectrum, though this may be more likely in other verticals such as an industry campus when the coverage and quality of national MNOs might not meet the requirements of a manufacturer, or V2X applications along roadsides far away from residential areas – noting that this is for a geographically limited area. There are cases in some markets of anchor tenants deploying specialist communications infrastructure to address their needs for example in public safety and train control systems. Whether such an approach is viable for complete transport corridor is beyond the scope of this project. The potential for small or specialist users to get access to spectrum is discussed in the section on regulation.

Daimler, and companies like it, is effectively becoming a mobile service provider, this is not a core activity for them. However, they have stepped into the gap in terms of connectivity coverage and quality that must clearly exist at the moment. They have been able to move more quickly than the traditional MNOs in terms of loosely integrating together a patchwork of networks in order to meet their needs. One may take the view that this loose integration may evolve in the orchestration of multiple networks in the future. The advent of 5G and NFV should make it technically easier to combine different infrastructures together and present one seamless service to the end-user as Daimler have been doing in a more limited way with today's technology.

On the one hand, this represents a challenge to the traditional MNOs under 5G because it would become easier for companies to manage a service and optimise performance across a range of networks. On the other hand, 5G should put MNOs in a better position to fill the gaps in wireless connectivity through delivering high quality services across multiple infrastructures and leveraging their inherent expertise in this area. This should reduce the need for companies like Daimler to operate as MSPs and allow them to back-off to the position of tenants with more or less network slice control as required.

However, Daimler and others may also benefit from facing fewer regulatory constraints than the traditional MNOs and this may help explain why they have been able to act more nimbly. For example, if an MNO did the equivalent of Daimler's optimised connectivity service, it could easily be seen as colluding with its peers and fall foul of competition law.

In that vein, Daimler has an interest in avoiding being placed under the same regulatory framework as the traditional MNOs, in much the same way as Facebook and Google have battled hard to avoid being classed as publishers and thus avoiding media regulations which would make them responsible for the content their users post on social media.

Today's MNOs could face substantial competition in the future MSP segment of the market. The risk is that suppliers who have specific ties to the vertical (in this case automotive) take the MNO out of the equation in terms of the client relation. Hence today's MNOs could get stuck as only one of a portfolio of wireless infrastructures chosen dynamically by the MSP and its vertical specialist partner.

On the other hand, the market has huge potential for growth and structures which exist today in 4G MTC may be swept away if better models emerge. From the 5G NORMA perspective, Daimler would be an ideal candidate to be a tenant and its specific needs could in theory be configured through a network slice. If the 5G NORMA architecture can demonstrably provide consistent and high quality performance, robustness, security and contribute to wider coverage, companies like Daimler and WirelessCar may focus more on pure applications and be willing to enter into more strategic partnerships with the infrastructure providers themselves.

We also note that there will be regulatory issues to be examined in terms of how infrastructures can be rolled into a service by MSPs, particularly when the vertically integrated firm operate both as infrastructure and service provider.

### 6.2.2 Airspan – alternative wireless infrastructure provider

In both Helsinki and Barcelona Airspan has deployed a series of trackside 4G small cells to carry operational traffic to and from metro trains and trams. Applications supported include mobile video surveillance, VoIP, data collection, automation and security applications.

These put high requirements on the system with the Helsinki network requiring peak data rates of 20 Mbit/s and on average 10 Mbit/s. Additional features required by this environment include full redundancy.

The systems are significant deployments and cover 40 km of track and over 50 base stations in the Helsinki case and 80 base stations and 20 trams in the Barcelona case. Airspan works with specialist system integrators in this field such as SICE in the Barcelona tram example.

Currently, there are few precedents for combining this type of independent, alternative infrastructure with that of the traditional MNO. However, 5G NORMA techniques should make this type of infrastructure sharing a lot easier and allow companies such as Airspan and the MNOs to derive mutual benefits. E.g. it could substantially reduce the cost of meeting the aspiration of ubiquitous (or even very extensive) 5G coverage for MNOs. Companies like Airspan will also benefit from utilising capacity that would otherwise be spare.

## 6.3 Today's mobile operators are already moving into the new stakeholder roles that we define for 5G NORMA

Figure 6-5 shows how MNOs and their partners fit into the stakeholder roles that should emerge with the advent of 5G. Although today's MNOs fit neatly into the stakeholder roles that correspond to areas where they are already strong - infrastructure provision and mobile service provision. The diagram shows that MNOs have also made inroads into the new stakeholder roles already. For example, through its subsidiary T-Systems, Deutsche Telekom is essentially acting as a tenant and vying for revenues further up the value chain from mobile connectivity.

Local or specialist (e.g. by vertical industry) infrastructures may also be deployed alongside national networks. However, we expect these will be largely complementary to the national networks of the MNOs. Moreover, as explained in the Airspan example, 5G will make it much easier for infrastructures to be combined together flexibly to meet the needs of end-users which may vary over time.

Mobile service provision is where today's MNOs have a lot of key strengths in managing networks, optimising network performance and accommodating rapidly growing demand. 5G NORMA innovations (adaptability and flexibility, enhanced performance management, ability to manage multiple infrastructures) will undoubtedly help MNOs in responding to the changing needs of the market including the opportunities in MTC and ultra reliable low latency communications (URLLC) services. However, this area of the value chain is also an area that could see substantial innovation particularly if other companies are able to move faster than the MNOs as new requirements for connectivity services become apparent.

Moreover, if MSPs do not need to be infrastructure players to do well in this segment of the value chain, it will be easier for new competitors to enter. Regulators will need to examine the competition issues around the interaction between standalone mobile service providers and vertically integrated infrastructure-mobile service providers.

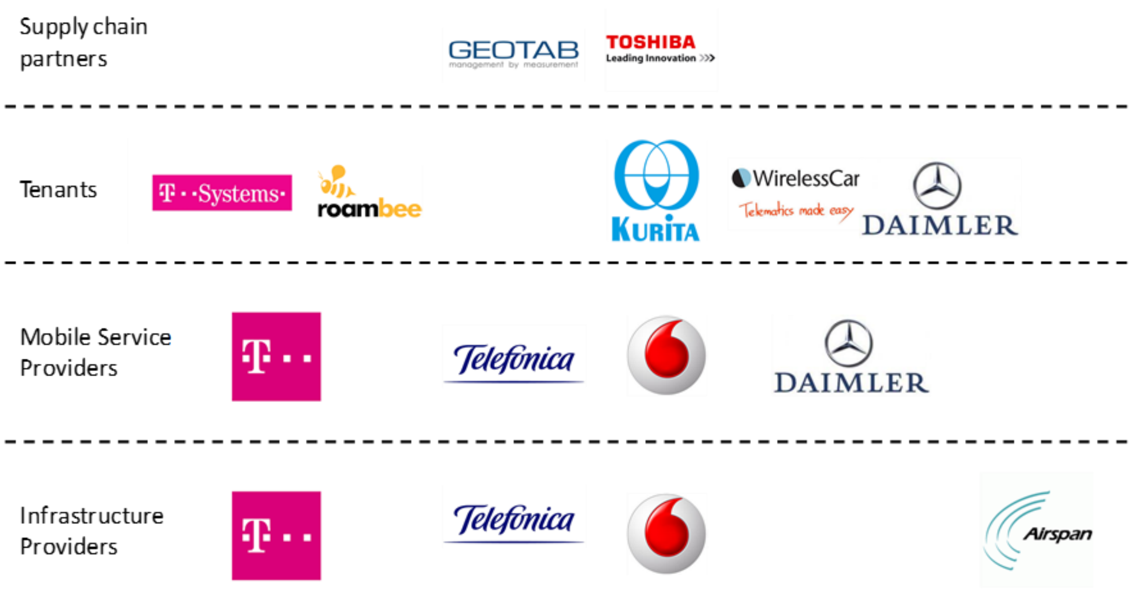



**Figure 6-5: Roles of IoT and MTC player examples mapped onto the new 5G NORMA stakeholder structure**

Another interesting question is whether some MNOs would consider splitting into separate infrastructure provider and mobile service provider entities. For example, infrastructure operation is already outsourced to third parties today in some cases, particularly in RAN sharing agreements, and this could be seen as an extension of that trend in the context of further infrastructure sharing. However, it would be a very significant step for any MNO to take.

A key competitive advantage of today's MNOs is their exclusive access to spectrum and at the moment integrating spectrum, infrastructure and service provision creates substantial barriers to new entrants. However, in the future operator strategies may change. MSPs will have to consider how they engage with tenants and how much they allow them to customise their network slices. Allowing greater customisation of slices may enable MSPs to charge more for services (extract more value) on top of the basic mobile connectivity service. However, the MSPs (and InPs) may be more cautious about opening up their networks and spectrum to others – perhaps only selling spare capacity (or infrastructure) to small players.

The tenants segment of the value chain could be very diverse. In some cases, the MNO will also be a tenant. The tenant may be a customer of the MNO: In a B2C situation the tenant could be a large end-user such as a train operating company. In a B2B context, the tenant could be a firm providing industry specific applications to companies in its industry and it may be able to capture synergies in integrating the mobile connectivity service into the specific services provided to the industry e.g. monitoring and data analysis of utility networks (such as water and waste).

We expect that this part of the value chain will see significant innovation in terms of the applications that are developed for end-users. This in turn will drive significant increases in value added. MNOs with a strong presence in systems integration may have a head start in addressing this segment. However, if applications develop in a very specialist or niche way, as opposed to mass market applications, the MNOs or their subsidiaries may have a hard time penetrating this market.

Finally, the supply chain partners provide other services, e.g. geolocation capabilities, data analytics, but do not necessarily have a strong relationship with end-user. As a result, it makes more sense for them to partner with MNOs (or vertical industry specialists who do have strong client relations) rather than to act as a tenant and target customers directly.

### 6.3.1 Summary of implications for mobile operator business model

The table below distils key elements of mobile operator business models from the examples listed above. The main alternative approaches for each element are set out and in the final column we assess whether the 5G NORMA innovations support or enhance either alternative.

**Table 6-1: Assessment of different business models**

| Key business model elements | Alternative 1 | Alternative 2 | Do 5G NORMA innovations support business model? |
|---|---|---|---|
| **Approach to providing end-to-end services, channels to market and addressing the wider value chain** | Collaborative and open network approach (i.e. giving partners the tools to manage or tailor network performance as tenants if required). Reach customers through: specialist partners in the verticals; innovative application & systems designers. The end-to-end service may be marketed as a joint venture rather than the MNO as a one-stop-shop. [See also revenue share potential] | The end-to-end service is branded as the MNO's. The MNO brings the necessary expertise in-house by organic development or acquisition of application and system developers. Alternatively, other providers are treated as suppliers rather than equal partners. The MNO may get a higher share of application development and systems integration sales. | 5G NORMA innovations such as multi-tenant model and network slicing support Alternative 1. Arguably, an open network approach suggests getting as many partners as possible onto a mobile service platform. |
| **Pricing models** | Revenue share and value based pricing – vertical specialists likely to understand better the value created for end-users and allow MNOs to reach a much broader base than they traditionally could. Note this does not necessarily imply that MNOs break into other parts of the value chain. MNOs need sufficient personnel to engage with partners and B2B clients to make the most of the opportunity. | Volume based pricing continuing the standard model of today (with exceptions for very large customers where more bespoke services can be offered). This strategy views connectivity as a commodity business. It will work best if accompanied by a push to maximise 5G cost savings and to get as many 5G tenants onto the network as possible to maximise data traffic revenues. | 5G NORMA network flexibility and adaptability supports Alternative 1. These innovations may be important for de-risking any move away from volume based pricing. 5G NORMA multi-tenancy and multi-service innovations (Evaluation Cases 2 & 3) support Alternative 2 in as far as they lead to real incremental cost savings over 4G or performance improvements that an MSP can generate additional value from. |

| Key business model elements | Alternative 1 | Alternative 2 | Do 5G NORMA innovations support business model? |
|---|---|---|---|
| **Cost savings and synergies in operating edge server networks** | Synergies in VNF servers and cloud based application design and operation. Most likely to be important where content and application is local and there are benefits from distributing data at the edge. E.g. V2I transmitting local road conditions to vehicles. | Taking on Google and Amazon in centralised servers is conceivable, but challenging. It is probably a step too far away from the MNOs' core business of network provision to be of relevance to the 5G NORMA innovations. | 5G NORMA innovations including the virtualisation of network functions and edge cloud architecture support Alternative 1. |
| **Role of competitors - applications providers, IT systems integrators, or vertically focused SPs** | Cooperate and compete with MNOs depending on whether they have close links to consumers and whether MNOs can add value e.g. global connectivity. | MNOs aim to control interaction with the customer as much as possible and limit third parties' ability to innovate in connectivity in order to counter the competitive threat. However, the overall applications market could be significantly smaller. Plus wider social benefits may be at risk which could lead to intervention (e.g. on open access) by governments. | 5G NORMA innovations support Alternative 1. If performance improvement under 5G NORMA architecture and 5G coverage promises are convincing, the need for the likes of Daimler etc. to dynamically switch between multiple networks should reduce and along with it, competition at the MSP level. |

We have also considered the potential impact on revenue of the business model choices which are open to MNOs. At this early stage, we make no firm recommendations since the evidence is limited. Instead, we list below some of the implications arising from our analysis that will need further study:

- The flexible, open network approach and the less flexible, competitor limitation approaches to tenants are clearly very different paths. They key question is how far an open approach will expand the whole market across the value chain compared to the closed approach and whether it will be better to have a smaller share of a larger market overall, or a larger share (as a result of moving up the value chain) of a smaller market. This is one area where more information (e.g. on 5G applications and the impact of flexibility for tenants on innovation) and research is necessary.
- Some smaller operators will not have the systems development and telematics expertise of the larger operators. For them the strategy of developing in-house expertise in order to capture a wider share of the value chain is less likely to be appropriate. Collaborative partnerships and open network models seem more likely to be successful.
- Regulators will need to consider the interaction between stand-alone MSPs or InPs and firms which are vertically integrated i.e. vertically integrated players should not favour their own subsidiaries in a way that would be harmful to or distort competition.
- The EC SMART project produced a high level quantification of the socio-economic benefits in 4 vertical industries including automotive [Ec17]. They identified benefits arising from B2C services and from B2B services. We have calculated the ratio of B2B

to B2C revenues from EC SMART's automotive forecasts to get a high level indication of the potential upside from B2B service in our forecast of V2X revenues. In [Ec17], consumer revenues from V2X are estimated at €22.7bn in 2030. B2B revenues equal €43.1bn in 2030, or 190% of B2C revenues. The B2B revenues comprise €20.8bn in "strategic benefits" to auto manufacturers in terms of telematics information to improve productions processes and €22.3bn of third party benefits such as insurance industry information which can be thought of as B2B2C services. Hence, there is substantial potential upside for revenue from B2B services and we consider this an important area for future study.

## 6.4 Implications for regulators and governments

### 6.4.1 Introduction

Regulators will be keen to ensure that the mobile regulatory framework responds to the significant changes that 5G will bring to the mobile market and value chain, and will be keen to create the right environment for the continued growth of the industry and the knock-on benefits for consumers and the wider economy. A number of key questions arise in relation to the 5G NORMA innovations, in particular around multi-tenancy and the emergence of new stakeholder roles:

- Whether any opportunities for anti-competitive behaviour may arise from companies that are vertically integrated across the new stakeholder roles?
- The implications of multi-tenancy for the regulation of shared resources and, in particular, should spectrum pooling and sharing network resources to a level similar to a multi-operator core networks (MOCN) approach as proposed in 4G networks be allowed?
- How do the new stakeholder roles affect existing regulation, e.g. on net neutrality, QoS and interference?
- Is there a need for a review of approaches to net neutrality in view of network slicing's ability to differentiate network performance for different sources of traffic?
- Is there a need to ensure that access to fibre for mobile operators is regulated in a way that allows mobile operators to deliver the maximum benefits for consumers and businesses whilst still providing a fair return to fibre network operators?

### 6.4.2 Regulation of access to mobile networks by tenants and vertically integrated operators

If a tenant competes with the national MSP, regulators will want to be sure that the MSP does not discriminate in favour of its own retail operations by charging the tenant higher prices or unduly restricting access to network functionality. Here we assume that the tenant is not another national retailer of mobile services, but is focused on a vertical market segment or niche.

- If competition among MSPs is effective – e.g. a minimum of three or four wholesale operators appears to be the norm in telecoms regulation – competition authorities should not normally have grounds to intervene.
- If there are less than three MSPs in a country or region, competition authorities might decide to regulate wholesale access agreements, or they might seek to deter anti-competitive behaviour by an "ex post" regulatory regime of investigations and fines where breaches of competition law are found to have been committed.

**<u>MSPs clearly have to strike a balance</u>** between maintaining the security and stability of their networks and opening access to the network as far as practicable for tenants (which provides flexibility and may stimulate innovation).

- More open access increases commercial and technical risks on the network and MSPs may judge the risks differently. More importantly, different approaches will have differing strategic implications for MSPs. MSPs may consider partnership with tenants as a way to facilitate greater innovation and expand the market for applications and content, while opening up opportunities for the MSP to take a share of revenue from further up the value chain. At the other end, the higher risk open access approach – which allows tenants maximum flexibility to innovate and maximises wholesale revenues for the MSP – may limit MSPs' opportunities to compete further up the value chain.

- It will be in the interests of MSPs to explain to regulators where technical factors, such as security and stability, as opposed to gaining a competitive advantage over rivals have influenced their decisions to restrict tenants' access to the network.

If MSPs follow a wholesale only strategy, then concerns over discrimination against tenants disappear. Wholesale only mobile operators are not common in today's mobile markets, particularly at the national level, and there is nothing yet to suggest that 5G will alter this.

- If there were a limited number of operators who could provide wholesale mobile access, i.e. one or two, regulators might be concerned that wholesale prices could be excessive. There may be pressure to introduce cost oriented pricing of wholesale services as is common today in wholesale access to fixed broadband services.
- In particular, where services providers such as BT in the UK have been found to have significant market power in these markets, regulators have accepted that facilities based competition e.g. parallel fixed broadband networks such as Virgin Media in the UK, have a limited impact on competition and have favoured measures such as local loop unbundling which allow other providers to compete with an incumbent, by permitting them to use the incumbent's access networks at reasonable prices.
- In the fixed network, this type of regulation took a substantial amount of time to become effective given that regulators had to understand the detailed technical and cost issues in fixed access networks for regulation to be effective. It might be better to maintain competition in wholesale mobile access, rather than allow a monopoly or duopoly to develop, because of the time and expense of developing effective regulation. Or put differently, the regulatory difficulties should be set against any potential benefits (e.g. cost savings) from allowing mobile service provision to become highly concentrated.

### 6.4.3 Shared access to spectrum and core network sharing

Here we assume that there are several national MSPs offering a similar range of services and sharing one common infrastructure in a similar but potentially deeper way than RAN sharing between MNOs today.

5G NORMA's multi-tenancy and NFV innovations offer greater opportunities for network sharing between national MSPs both from a technical and economic viewpoint – as is analysed in Evaluation Case 2. Hence, the 5G NORMA architecture should increase the benefits for MSPs from network sharing compared to the current situation.

However, regulators' attitudes to sharing vary across the EU. While passive and active RAN sharing are generally accepted, though competition requirements need to be satisfied, core network sharing and frequency pooling are far less accepted. Core network sharing and spectrum pooling are prohibited in Germany, and in many countries no commercial agreements have been reached. The attitude of many regulators such as Ofcom in the UK has been not to prohibit, but to state that approval would be subject to there being no concerns over the impact on competition.

Spectrum pooling has been allowed in a few EU Member States including Denmark, Sweden and Hungary. In the latter for example, two MNOs, Telenor and Magyar Telekom, have a sharing arrangement whereby one provides the mobile sites and infrastructure for the west of the country and the other one for the east (excluding Budapest). A leasing arrangement for 800 MHz spectrum is in place between the two and this is thought to have benefitted Hungary and led to a high level of LTE coverage nationally.

Regulators will have to assess whether this enhanced network sharing carries greater risks of enabling anti-competitive behaviour – specifically collusion – between national MSPs to the detriment of consumers. Regulators will assess these risks through the same frameworks applied to network and spectrum sharing today, namely the extent to which service providers are able to share strategic information as a result of the arrangements and, critically, to coordinate prices (and to raise them above the level in a non-sharing scenario). In the few cases around the world where this happened, sometimes competition remedies have been imposed before approving a deal as in Denmark (2G/3G/4G all Denmark in scope), and Finland (800 MHz, rural + later 2G/3G). In Sweden (3G/4G all Sweden), Canada (3G/4G in parts of Canada) and Hong Kong (2G/3G/4G across Hong Kong) agreements were approved without remedies.

MSPs are likely to take these concerns into account in the way in which multi-tenancy is implemented and this should be an area of further research for regulators so that the right framework is in place before the commercial launch of these networks.

In addition to spectrum pooling, there may be benefits for regulators to encourage more spectrum sharing through shared access, such as Licensed Shared Access (LSA), trading and leasing in existing licensed spectrum. Promoting increased access to spectrum in this way has been acknowledged by the European Commission as an enabler for cost savings for MNOs and affordable connectivity [Ec12]. It is also described as supporting innovation and market entry [Ec16].

- Firstly, this would facilitate self-provision of infrastructure in areas where it is either uneconomic for MNOs to deploy infrastructure, or where it may be more efficient for the user to do so, for example an indoor network in a factory campus or warehousing facility that is not in a residential population area, or a roadside network that is similarly far from residential properties. These cases may be particularly amenable to low power shared access approaches to spectrum.
- Secondly, a similar type of self-provisioning could be adopted by enterprise and public buildings where improved coverage or capacity to tenants and visitors requires a dedicated indoor network that individual MNO's alone would not be prepared to fund.
- Thirdly, enabling more low power shared access spectrum would reduce barriers to entry for some new entrants, particularly those trying to exploit innovative niches who may be able to act more quickly than larger nationally focussed operators. Such niche operators would then have the choice of deploying their own infrastructure or taking a network slice from an MSP if available (or a combination of both).

### 6.4.4 Which players should be subject to regulation in light of the new stakeholder roles?

Companies whose main sector of activity lies outside communications – such as automotive manufacturers – are unlikely to create concerns over a distortion of competition because:

- They are likely to be relatively small in relation to the overall market for mobile access and hence unlikely to wield substantial market power;
- National MSPs will always provide another source of competition to those focusing on particular niches.

Where companies aggregate connectivity from a number of national or local MSPs to optimise network performance for their end-users - e.g. the Daimler and WirelessCar service described above – regulators may well look on this differently if the aggregator is a vertical rather than one of today's MNOs.

In terms of other types of communications sector regulation, such as QoS, net neutrality consumer protection, etc., regulators will have to consider which stakeholder (InP, MSP or tenant) should be subject to regulation. More generally, the InP-MSP-tenant relationship opens up the question of where the most appropriate place in the supply chain is to place these regulations.

Consumer protection regulation may fall most appropriately on the tenant because they are likely to own the relationship with the end consumer.

QoS regulation is less clear. The MSP will have the ultimate influence on QoS, however, it may also depend on the degree of flexibility given to the tenant. Alternatively, placing the responsibility for QoS on the tenant will encourage tenants to develop service level agreements that correctly apportion the risk between them and the MSP/InP. Until MSP strategies and commercial arrangements start to become clearer, it will be difficult to answer this question.

Net neutrality regulation is likely to fall on the MSPs. There will be greater potential for offering differentiated services to tenants in 5G NORMA based networks and it will require a sophisticated analysis to separate where discrimination between tenants is actually beneficial for consumers from those cases where it could be harmful. The possible need for changes in net neutrality regulation is discussed in the separate section below.

More technical regulations such as prevention of harmful interference, could fall on either the InP or the MSP depending on what each of them provides. For example, if the InP only provides sites and the MSP controls the radio equipment, the MSP would be responsible for preventing harmful interference.

### 6.4.5 The regulatory implications of network slicing and differentiated traffic management (net neutrality)

Network slicing enables MSPs to offer highly differentiated services to tenants. The added flexibility might significantly increase innovation, expand the range of applications offered and create significant value for end-users. However, this might imply that traffic for some services or applications may be managed differently to others and this could contravene EU net neutrality rules against traffic management.

A good example of the EU approach to net neutrality is given by ARCEP, the French regulator, which has published a set of non-binding recommendations providing general direction and principles [Arc10].

ARCEP states that as a general rule, there should be no differentiated traffic management in access to the internet. Where there might be exceptions to this principle, they must still comply with general principles of relevance, proportionality, efficiency, non-discrimination between parties and transparency.

ARCEP’s position illustrates the EU interpretation of net neutrality which focuses on protection of consumers (and content and application providers) from unfair discrimination and QoS rather than an all-out ban on any practice that does not treat communications traffic equally. It recognises that there may be beneficial effects, e.g. reducing the overall level of congestion in a network, from service providers managing user traffic flows.

It can be clearly argued that network slicing will create lots of additional value for consumers without harming any one group of users even though some tenants may be able to purchase network slices with different traffic management characteristics (i.e. performance requirements) than others. Given the way in which net neutrality rules are phrased in EU, network slicing would probably fit into the framework as an exception to general net neutrality principles.

However, this could create uncertainty for mobile operators and content and application providers. In theory, each new network slicing agreement might have to be considered under the rules, although we note that currently the trend appears to be to investigate where complaints are raised rather than on a case by case basis.

National regulators and the EU should consider whether, given the potential benefits of network slicing, there is a better approach that protects content and application providers, and consumers, from abuse by operators while promoting the innovation and service creation that network slicing can deliver.

### 6.4.6 Creating the regulatory framework to facilitate access to fibre for 5G networks

Easy access to fibre or the ability to deploy new fibre quickly and at the lowest possible cost would be of significant benefit in deploying a 5G network based on the 5G NORMA architecture given the need for high speed data transport between nodes in the cloudified infrastructure layer.

Dark fibre is one option for mobile operators and reference offers for access to dark fibre generally offer access on favourable terms. However, the availability of dark fibre varies between countries and within countries so it is only a partial solution to the need for capacity.

There are also managed connectivity products, such as BT's Gigabit Ethernet Access products. These products vary in the extent to which they are cost oriented. Undoubtedly a move towards more cost orientation across the board would bring down fronthaul and backhaul prices and benefit 5G deployment. However, regulators have to take into account the interests of fixed operators too and this may limit the pressure from regulators to reduce charges for these products towards costs.

The alternative to purchasing dark fibre or managed connections from fixed operators is for mobile operators to deploy their own fibre networks. Passive infrastructure access, or access to ducts and poles, is key to this. Some regulators such as in France, Portugal and Spain have very progressive regulatory frameworks for passive infrastructure access, whereas in other countries, such as Germany and the UK, progress has been slower. [Wik17] provides a good discussion of this and the wide disparity in approaches is highlighted by the following examples:

- Portugal and Spain have been very successful in promoting fibre rollout for two reasons. Charges for access to duct and poles have been cost oriented, but fair. Further, they put a lot of weight on essential but ancillary issues which has streamlined the process, e.g. easy automated access to the incumbent's duct planning databases, requirements to provide alternative access if ducts are full, tight deadlines for delivering products etc. In Spain and Portugal, these measures really began to take hold from 2009 onwards (though introduced in Portugal even earlier in 2004). A member of the Portuguese regulator attributes the flourishing of alternative fibre networks in Portugal (e.g. by Optimus and Vodafone) to the regulations [Itu14].
- In contrast, the UK had a more light touch approach and only now in 2017 has it launched a consultation on introducing the type of duct and pole access regime that has been so successful in Iberia and other areas.

# 7 Conclusions

Finally, this section captures conclusions and key findings from our study.

**Key findings regarding the commercial case for eMBB only single tenant networks based on the 5G NORMA proposed architecture**

Within this study we have analysed the CAPEX and OPEX incurred over an 11-year period from 2020 to 2030 for deploying a C-RAN virtualised network compared with a D-RAN network to deliver eMBB services to consumer portable devices in a central London example environment. Both networks were based on a typical MNO with an 18% share of the eMBB market. We conclude that costs on an 11-year Total Cost of Ownership (TCO) basis are similar between the two options with C-RAN requiring higher CAPEX but lower OPEX for this scenario and found only a very marginal TCO penalty with C-RAN (approximately 2%). Sensitivity analysis showed this conclusion stood largely unchanged for the traffic growth levels, transport costs and edge cloud site costs ranges explored.

When the above eMBB only network costs were combined with our forecast eMBB revenues for the central London example area this showed a 6% return on investment (ROI) for our medium traffic and revenue scenario. Deploying a C-RAN network appeared to make little difference to the business case compared to a D-RAN network. However, we note that there is risk to the future eMBB business case with this positive ROI being very sensitive to:

- Revenue scenario
- Traffic growth

We note that within the eMBB market there is very limited scope for increased revenues per subscriber (which are driven by a consumer’s willingness to pay). However, there is significant scope for variation in eMBB traffic levels based on the range of forecasts available. This means that in a high revenue and high traffic scenario the ROI for eMBB over the study period could reduce to -11.9% due to limited scope for increased revenue but high network costs due to higher demand. However, in our low revenue and low traffic scenario network costs are greatly reduced while revenues are assumed to remain at existing levels which leads to a 35% ROI.

**Key findings regarding the commercial case for eMBB only multi-tenant networks based on the 5G NORMA proposed architecture**

Our cost analysis of two existing site portfolios becoming a shared network for two Mobile Service Providers (MSPs) (each with a typical eMBB market share of 18% each) has shown a reduction in TCO of 14% between 2020 and 2030. This is without decommissioning and consolidation of sites but rather applying multi-tenancy support or sharing (in terms of masts, antennas, RRHs, baseband processing, spectrum and core network) to any new or upgraded sites that merit it in this timescale. These shared sites have access to pooled spectrum from the parties sharing the site and hence are higher capacity than in dedicated sites with access only to spectrum from one party. The ability to deploy these higher capacity multi-tenant sites means that site densification can be done more efficiently than in dedicated networks with a reduction in the total number of antenna sites needed. This reduction in site count leads to savings in large cost components such as site rental.

Our sensitivity analysis shows that there is a balance to situations where sharing is more beneficial. If demand growth is low and site densification is not required there is less opportunity to deploy higher capacity multi-tenant sites. Instead consolidation of existing site portfolios and site de-commissioning is needed to see sharing gains in the shorter term. However, in a high demand case the macrocell layer may already be very dense in which case small cells, which are more challenging to share, may be relied upon more to relieve demand hotspots. Additionally, the sharing benefit to the 11-year TCO will become capped regardless of the number of MSPs sharing a site due to limitations on the amounts of spectrum that can be pooled whilst still maintaining safe radiation levels. In our analysis assuming 100 MHz of spectrum per MSP, cost savings were capped at approximately 15% regardless of expanding sharing from 2 to 3 or 4 MSPs due to no more than an assumed spectrum pool of 200MHz being permitted at any shared site.

While sharing of network infrastructure and equipment costs can be realised already with today's networks 5G multi-tenant networks take sharing to another level. Within 5G multi-tenant networks resources can be shared at a more granular level than today. Also, MSPs can implement their own sets of virtualised network functions on the shared network resources and as such can have more control and less compromise in terms of the quality of experience delivered.

In terms of our business case assessment for eMBB, this improved for our medium scenario from an ROI of 6% to 17% when sharing amongst two MSPs was applied. Therefore, multi-tenancy stands to reduce some of the risk observed in the eMBB only case observed earlier.

**Key findings regarding the commercial case for multi-service networks based on the 5G NORMA proposed architecture**

Finally, our cost analysis examined the impact of applying network slicing to support non-eMBB services such as smart meter services and Vehicle to Infrastructure (V2I) services (including high bandwidth infotainment, low bandwidth massive Machine Type Communications (mMTC) assisted driving services and high reliability semi-automated driving services). In the case of these services a 100% market share was assumed within the study area.

The cost of the network was mainly eMBB-driven with other non-eMBB services only contributing small volumes of traffic (i.e. with smart meters, semi-automated driving and assisted driving traffic volumes combined being only less than 4% of the eMBB traffic volume in total over the study period). However, we observed a disproportionate increase in the cost when compared to the demand of some non-eMBB services. For example, there is a 0.0070% increase in overall network traffic when the smart meter traffic is introduced, but a worst case 5.2% increase in the network cost, due to the early initial investment for building the sub-1GHz capability into the network to support deep indoor penetration.

Other non-eMBB services, were more easily accommodated on the existing eMBB network. These included semi-automated driving where the existing site density in the study area combined with gains from vehicle mounted antennas were enough to provide the higher coverage confidence required for these services without any repurposing of the network needed and no observed impact on the network's TCO over the study period. Assisted driving services, with a slightly higher traffic increment over eMBB services than semi-automated driving of 1.9%, caused network densification in hotspot areas to occur a year earlier than in the eMBB only scenario resulting in a 2.5% increase in costs.

Combining the cost of delivering these new services with their potential to generate new revenue streams shows that there is potential to moderately improve the ROI compared with the baseline eMBB only case and hence de-risk this case further (although not to the same extent as the benefit of multi-tenancy for the cases examined). ROI improvements over the baseline eMBB only single tenant case of 3%, 6%, 7% and 10% were observed for combining eMBB with each of smart meter, assisted driving, infotainment and semi-automated driving respectively.

In our multi-service analysis, we have considered new non-eMBB services that are currently envisaged and that we believe would add most value in our smart city setting. However, as mobile networks continue to evolve and new applications for mobile services continue to emerge there may be more opportunities to increase the value added by multi-service support in mobile networks than that shown here. Further cost reductions in introducing support for services with challenging coverage and reliability requirements may also be possible via virtual network densification made easier via multi-tenancy in 5G NORMA networks as described in Deliverable D3.3 [5GN-D33]. However, given the existing high density of sites in our study area we have not included this effect in our analysis here.

**Key findings regarding the socio-economic case for multi-service networks based on the 5G NORMA proposed architecture**

Our research suggests that the social and wider economic benefits of multi-service mobile networks are substantial. The greatest benefits are likely to come from smart energy, V2I services and increases in productivity related to eMBB and services specific to the verticals, including those falling under Industry 4.0 and others (but not covered in detail in this study). They are of similar orders of magnitude to our revenue forecasts for these services included in our commercial assessment and in some cases, e.g. smart energy, they are substantially higher.

There are several indications as to where intervention may be appropriate, although further research will be necessary, particularly for lower population density areas, to refine this initial research:

- There is a question mark over whether revenues arising from eMBB will continue to be sufficient to cover the cost of infrastructure by itself although the commercial business case is improved by the economies of scope from deploying multi-service networks.
- Although the data volumes involved in smart energy are small compared to other services such as eMBB, it will need nation-wide, reliable coverage. Our business case assessment suggests that there could be material risks to the business case in areas less densely populated than Central London, therefore there is a risk that the market might not be able to provide the necessary coverage on a nation-wide basis. Much depends on how the energy market itself develops and whether microgeneration and electric vehicle charging take off and require dense sensor and actuator networks. We recommend that analysis of the risks to adequate smart grid provision should be incorporated into the strategy for the energy sector and the transition to a low carbon economy.
- V2I services are likely to be commercially viable particularly in the most densely populated cities. However, it is not clear whether the same would be true of the road network outside these areas, particularly given that the quality of mobile coverage on these roads can already vary significantly.

**Key findings regarding implications for stakeholders including MNOs, verticals and regulators of 5G virtualised networks such as 5G NORMA**

The 5G NORMA based architecture enables a new multi-tiered stakeholder model made up of tenants (who acquire mobile services and manage the relationship with end users), mobile service providers (MSPs) (who implement end-to-end network functionality to deliver mobile services) and infrastructure providers (who manage and provider the sites, physical equipment and interconnectivity that MSPs can implement their virtualised network upon).

Given the challenge that the mobile industry faces of flat or declining revenues but growing demand and hence network costs, we have examined how MNOs are already re-positioning themselves within the ecosystem to engage with verticals, provide higher value mobile services and hence generate new and more efficient revenue streams.

We also examine the implications for regulators and governments in ensuring the right regulatory environment is in place to ensure that the social benefits and innovative ecosystems promised by multi-service networks such as those proposed by 5G NORMA are realised.

# 8 References


[22.886] 3GPP, "Study on enhancement of 3GPP Support for 5G V2X Services", TR 22.886 v15.1.0, March 2017.

[23.251] 3GPP, "Network sharing; architecture and functional description", TS 23.251 V14.0.0, March 2017.

[5GN-D21] 5G NORMA, "Deliverable D2.1, Use cases, scenarios and requirements", October 2015.

[5GN-D22] 5G NORMA, "D2.2 Evaluation methodology and KPIs, evaluation

architecture design and socio-economic analysis – intermediate report", Oct. 2016

[5GN-D32] 5G NORMA, "Deliverable D3.2, 5G NORMA network architecture – Intermediate report", January 2017.

[5GN-D33] 5G NORMA, " Deliverable D3.3, 5G NORMA network architecture – Final report", October 2017.

[Ana16] Analysys Mason, "Financial impact of ECC changes", May 2016.

[Arc10] ARCEP, http://www.arcep.fr/uploads/tx_gspublication/net-neutralite-orientations-sept2010-eng.pdf, 2010

[Bbc16] BBC News, "A day in the life of an Amazon delivery driver", November 2016.

[BC12] Bhaumik, S, et al. CloudIQ: A Framework for Processing Base Stations in a Data Center. MobiCom'12, August 22–26, 2012, Istanbul, Turkey.

[Bcg15] Boston Consulting Group, "Industry 4.0: The Future of Productivity and Growth in Manufacturing Industries", April 2015, https://www.bcgperspectives.com/content/articles/engineered_products_project_business_industry_40_future_productivity_growth_manufacturing_industries/

[BGB+17] Bega, M. Gramaglia, A. Banchs, V. Sciancalepore, K. Samdanis, X. Costa, "Optimising 5G infrastructure markets: The Business of Network Slicing", in Proceeding of IEEE INFOCOM 2017, Atlanta (USA).

[Cbr15] Computer Business Review, "IOT deal sees Germany luxury car maker building APIs", 2105, http://www.cbronline.com/news/internet-of-things/daimler-gets-iot-smart-by-linking-cars-to-enterprise-systems-4713572/

[Ccc17] Committee on Climate Change, https://www.theccc.org.uk/tackling-climate-change/reducing-carbon-emissions/carbon-budgets-and-targets/

[Cis16] Cisco VNI, "Cisco Visual Networking Index: Global Mobile Data Traffic Forecast Update, 2016–2021 White Paper", http://www.cisco.com/c/en/us/solutions/collateral/service-provider/visual-networking-index-vni/mobile-white-paper-c11-520862.html

[Cpr15] CPRI, "Common Public Radio Interface (CPRI); Interface Specification," v7.0, October 2015

[Cpr17] CPRI, "Common Public Radio Interface (CPRI); eCPRI Interface Specification," v1.0, August 2017

[CSB+16] Chhaya, Sharma, Bhagwatikar and Kumar, "Wireless Sensor Network Based Smart Grid Communications: Cyber attacks, Intrusion Detection Systems and Topology Control", December 2016, www.mdpi.com/2079-9292/6/1/5/pdf.

[Dbe16] Department for Business, Energy and Industrial Strategy, UK, Smart meter roll-out cost-benefit analysis, 2016, https://www.gov.uk/government/publications/smart-meter-roll-out-gb-cost-benefit-analysis

[Dec15] Department of Energy and Climate Change, UK, UK local authority and regional carbon dioxide emissions national statistics https://www.gov.uk/government/statistics/uk-local-authority-and-regional-carbon-dioxide-emissions-national-statistics-2005-2013

[Dft12] Department for Transport, "Setting local speed limits", July 2012.

[Dft15] Department for Transport, UK, Reported casualties by severity, Great Britain, 2005 - 2015 - Table RAS30003, https://www.gov.uk/government/publications/reported-road-casualties-in-great-britain-main-results-2015

[Dft16] Department for Transport, UK, WebTAG Databook Spring 2016 – https://www.gov.uk/government/publications/webtag-tag-data-book-july-2016

[Dge17] EC, DG Energy, 2017, https://ec.europa.eu/energy/en/topics/markets-and-consumers/smart-grids-and-meters

[Dot14] UK DOT Report. "Road Traffic Estimates: Great Britain 2014", UK, Department for Transport, Dec 2014.

[Ear12] Ernst & Young, Smart Grid: a race worth winning, 2012 http://www.ey.com/Publication/vwLUAssets/Smart-Grid-A-race-worth-winning/$FILE/EY-Smart-Grid-a-race-worth-winning.pdf

[Ec15] EC, "Identification and Quantification of Key socio-economic data for the strategic planning of 5G introduction in Europe", 2015.

[Ec16a] EC, 5G Action Plan, 2016, https://ec.europa.eu/digital-single-market/en/5g-europe-action-plan.

[Ec16b] EC, "Connectivity for a Competitive Digital Single Market: Towards a European Gigabit Society", 2016, https://ec.europa.eu/digital-single-market/en/news/communication-connectivity-competitive-digital-single-market-towards-european-gigabit-society

[Epe12] European PPP Expertise Centre , "Broadband: Delivering next generation access through PPP", 2012.

[Eri16] Ericsson, "Ericsson mobility report for November 2016", https://www.ericsson.com/assets/local/mobility-report/documents/2016/ericsson-mobility-report-november-2016.pdf

[Ep15] European Parliament, Industry 4.0, Digitalisation for productivity and growth, 2015, http://www.europarl.europa.eu/thinktank/en/document.html?reference=EPRS_BRI%282015%29568337

[Eup12] Analysys Mason for the European PPP Expertise Centre, "Broadband: Delivering next generation access through PPP", 2012.

[Evs16] Evening Standard, “Revealed: how average speed of London traffic has plummeted to just 7.8mph”, December 2016.

[Gsm12] GSMA, “Mobile Infrastructure Sharing”, Report, 2012.

[Gsm13] GSMA, Connected Car Forecast: Global Connected Car Market to Grow Threefold Within Five Years, Feb 2013

[Gsm16] GSMA, Telefónica helps car rental firms boost revenue, 2016 https://www.gsma.com/iot/telefonica-helps-car-rental-firms-boost-revenue

[Hmt13] UK Treasury, The Green Book: appraisal and evaluation in central government, 2013, https://www.gov.uk/government/publications/the-green-book-appraisal-and-evaluation-in-central-governent

[G.826] ITU-T, “End to end performance parameters and objectives for international, constant bit rate digital paths and connections”, ITU-T recommendation G.826, December 2002.

[M.2135-1] ITU-R, “Guidelines for evaluation of radio interface technologies for IMT Advanced”, ITU-R M.2135-1, December 2009.

[Itu14] ITU News, Meeting the demand for broadband capacity in Portugal: Interview with Professor João Confraria Member of the Board of ANACOM, 2014, https://itunews.itu.int/En/5222-Meeting-the-demand-for-broadband-capacity-in-Portugal.note.aspx

[M.2370-0] Report ITU-R M.2370-0, “IMT traffic estimates for the years 2020 to 2030”, M series, Mobile, radiodetermination, amateur and related satellite services, July 2015.

[Itv15] ITV News, “Traffic lights up across the city – how many in your area?”, October 2015, http://www.itv.com/news/london/2015-10-19/traffic-lights-up-across-the-city-how-many-in-your-area/

[JH10] Jespersen, S. T., & Hansen, E. S., “The socio-economic value of digital infrastructures.” 2010, http://www.danishenergyassociation.com/Theme/Digital_Infrastructures.aspx

[Jrc14] EC, EC’s Institute for Energy and Transport, Joint Research Council, Smart Grid Projects Outlook 2014, http://ses.jrc.ec.europa.eu/sites/ses.jrc.ec.europa.eu/files/u24/2014/report/ld-na-26609-en-n_smart_grid_projects_outlook_2014_-_online.pdf

[Kpm15] KPMG, Connected and Autonomous Vehicles: The UK Economic Opportunity”, March 2015, https://www.smmt.co.uk/wp-content/uploads/sites/2/CRT036586F-Connected-and-Autonomous-Vehicles-%E2%80%93-The-UK-Economic-Opportu...1.pdf

[KQ11] Kivleniece I. and Quelin B., “Creating and Capturing Value in Public-Private Ties: A Private Actor’s Perspective”, The Academy of Management Review, September 2011.

[Mac15] Machina Research, M2M growth necessitates a new approach to network planning and optimisation, 2015.

[MET14-D66] METIS D6.6 “Final report on the METIS 5G system concept and technology roadmap,” ICT-317669 METIS Deliverable 6.6, Version 1, May 2014

[Mob17] Mobile Europe, 20 August 2017, https://www.mobileeurope.co.uk/press-wire/three-quarters-of-companies-would-pay-5g-premium-survey-finds

[Ngm16] NGMN, “Description of Network Slicing concept”, September 2016, available at https://www.ngmn.org/uploads/media/161010_NGMN_Network_Slicing_framework_v1.0.8.pdf

[Nia15] Niaein,N. “Processing Radio Access Network Functions in the Cloud: Critical issues and modelling”. ACM International Workshop on Mobile Cloud Computing and Services (MCS), 2015. http://www.eurec16om.fr/en/publication/4640/download/cm-publi-4640.pdf

[Nok16] Nokia White Paper, “Ten key rules of 5G deployment”, 2016, http://resources.alcatel-lucent.com/asset/200006

[Ofc07] Ofcom, Choice, competition, innovation: Delivering the benefits of the Digital Dividend, 2007, https://www.ofcom.org.uk/about-ofcom/latest/media/media-releases/2007/choice-competition-innovation-delivering-the-benefits-of-the-digital-dividend

[Ofc16] Ofcom, "Mobile Data Strategy - update on our strategy for mobile spectrum", June 2016, https://www.ofcom.org.uk/__data/assets/pdf_file/0033/79584/update-strategy-mobile-spectrum.pdf

[Ofc16b] Ofcom, UK, “The Communications Market Report 2016”. https://www.ofcom.org.uk/research-and-data/cmr/cmr16

[Ofc17] Ofcom, "Communications Market Report - August 2017", August 2017.

[Ons14] Office for National Statisitics, “UK local authority and regional carbon dioxide emissions”, 2014, https://www.gov.uk/government/statistics/uk-local-authority-and-regional-carbon-dioxide-emissions-national-statistics-2005-2013

[Ons16] Office for National Statistics, Road Freight Statistics, 2016, https://www.gov.uk/government/statistics/road-freight-statistics-2016

[Ons17] ONS, Annual Business Survery, 2017, https://www.ons.gov.uk/businessindustryandtrade/business/businessservices/bulletins/uknonfinancialbusinesseconomy/previousReleases

[Ope15] Openreach Local Loop Unbundling costs. https://www.openreach.co.uk/orpg/home/products/pricing . Accessed March 2017.

[Ost13] A. Osterwalder, Y. Pigneur, Business Model Generation. Hoboken, NJ: Wiley, 2013.

[PPF+17] C. Pereira, A. Pinto, D. Ferreira and A. Aguiar, "Experimental Characterization of Mobile IoT Application Latency," in IEEE Internet of Things Journal, vol. 4, no. 4, pp. 1082-1094, Aug. 2017.

[RB12] Rohman & Bohlin, Does broadband speed really matter for driving economic growth? Investigating OECD countries, Chalmers University Working Paper, April 2012, SSRN, Electronic Journal, http://dx.doi.org/10.2139/ssrn.2034284

[Rog62] Rogers, E. M., “Diffusion of Innovations”, 1962

[SCS16] K. Samdanis, X. Costa-Perez, V. Sciancalepore, “From network sharing to multi-tenancy: The 5G Network Slice Broker”, IEEE Communications Magazine, vol. 54, no. 7, pp. 32-39, Jul. 2016.

[Sha+12] Shafiq et al., “A first look at cellular machine-to-machine traffic – large scale measurement and characterization”, in Proc. ACM SIGMETRICS Perform. Eval. Rev., 2012, pp. 65–76.

[Sqw14] SQW and Real Wireless, “Economic Impacts of Mobile Communications in Scotland”, Report to the Scottish Government, January 2014.

[RSA+16] J. Rendon Schneir, A. Ajibulu, I. Berberana, G. Zimmermann, and C. Chambers, “A cost model for a 5G network“, 27th European Regional Conference of the International Telecommunications Society (ITS), Cambridge, United Kingdom, 8th–10th September 2016.

[Tel11] The Telegraph, “Mapped: how the country’s population changes during a work day”, based on Census 2011 data.

[Tel13] Daily Telegraphy, 2013, http://www.telegraph.co.uk/finance/newsbysector/energy/10243513/O2-and-Arqiva-win-2.1bn-smart-meter-contracts.html

[Tfl12] Transport for London, "Roads Task Force – Technical Note 14 Who travels by car in London and for what purpose? ", 2012, http://content.tfl.gov.uk/technical-note-14-who-travels-by-car-in-london.pdf

[Tfl12b] Transport for London Surface Transport Traffic Analysis Centre, “Traffic levels on major roads in Greater London 1993 – 2010”, March 2012

[Tfl14] University of Westminster for TfL, London Freight Data Report: 2014 Update, December 2014, http://content.tfl.gov.uk/london-freight-data-report-2014.pdf

[Tfl15] TfL, Surface Intelligent Transport System, June 2015 http://content.tfl.gov.uk/fpc-20150730-part-1-item08-sits.pdf

[TS17] T-Systems press release, , From whiteboard to dashboard in four weeks, Jan 2017, https://www.t-systems.com/de/en/about-t-systems/company/newsroom/news/news/shipment-monitoring-522584

[Vir17] Virral, G., “RTT TECHNOLOGY TOPIC”, April 2017, http://www.rttonline.com/tt/TT2017_004.pdf

[Vod17] Vodafone Financial Statements, 2017, http://www.vodafone.com/content/annualreport/annual_report17/downloads/Vodafone-financial-statements-2017.pdf

[Web16] Webb. W., “The 5G Myth: And why consistent connectivity is a better future”, ISBN: 1540465810.

[Wik16] WIK-Consult, “Network Sharing im Mobilfunk und Festnetz-Mobilfunk-Konvergenz in der Schweiz“, Report for the Government of Switzerland, August 2016.

[Wik17] WIK-Consult, “Best practice for passive infrastructure access”, 2017.

[Zet17] Zeetta Networks, “Bristol is Open”, article from website http://www.zeetta.com/bristol-is-open/ visited October 2017.

# 9 Appendix A – Evaluation Case 3 – performance, coverage and capacity requirements per service

This appendix reproduces the performance, capacity and coverage requirements tables for the range of services considered under Evaluation Case 3 from [5GN-D33].

**Table 9-1: Performance requirements for services in Evaluation Case 3 [5GN-D33]**

| Service component | User Experienced Data Rate | Latency | 5G NORMA improvements against legacy |
|---|---|---|---|
| **eMBB – consumer portable devices** | 10 Mbit/s DL/UL | 100 ms | Improved QoE |
| **V2I – infotainment (eMBB)** | 10 Mbit/s DL | 100 ms | Improved QoE |
| **V2I – semi-automated driving (uMTC)** | 0.5 Mbit/s DL/UL | <100 ms | More steady and lower latency, improved service coverage |
| **V2I – assisted driving (mMTC)** | 0.5 Mbit/s DL/UL | <100 ms | More steady and lower latency, improved service coverage |
| **Environmental monitoring, waste management, and congestion control (mMTC)** | 2 bit/s UL | > 50 ms | Improved outdoor coverage |
| **Smart meters - sensor data, meter readings, individual device consumption (mMTC)** | 2 bit/s UL | > 50 ms | Improved indoor coverage, more efficient protocols for small data packages |
| **Smart grid sensor data and actuator commands (mMTC)** | 2 bit/s UL | > 50 ms | Improved outdoor coverage |
| **Logistics – sensor data for tracking goods (mMTC)** | 2 bit/s UL | > 50 ms | Improved outdoor coverage |

**Table 9-2: Coverage and capacity requirements for services in Evaluation Case 3 [5GN-D33]**

| Service component | Data volume | Number of devices | Coverage |
|---|---|---|---|
| **eMBB – consumer portable devices** | On average, each device consumes 0.23 GB per day in 2020 growing to 2.85 GB by 2030 (29% CAGR) | 2020:<br>43k per km$^2$<br>2030:<br>47k per km$^2$ | 95% Outdoor |
| **V2I – infotainment (eMBB)** | 1 GB-25 GB per day per car (2020-2030) | On average 325 active vehicles on roads per km$^2$ | 95% (vehicles, outdoor) |
| **V2I –semi-automated driving (uMTC)** | On average 52 MB consumed per day per car in study area in 2021 growing to 1,503 MB per day per car in 2030 (45% CAGR)<br>Note 0% uptake in 2020 so on average 0 demand per car for this service. | On average 325 active vehicles on roads per km$^2$ | 99.9% (Vehicles, outdoors) |
| **V2I – assisted driving (mMTC)** | On average 52 MB consumed per day per car in study area in 2020 growing to 1,711 MB per day per car in 2030 (42% CAGR) | On average 325 active vehicles on roads per km$^2$ | 95% (vehicles, outdoor) |
| **Environmental monitoring, waste management, and congestion control (mMTC)** | On average 229 B per day per roadside item (i.e. traffic lights, road signs, bins etc.) in 2020 growing to 1,516 B per day per roadside item by 2030 (21% CAGR) | 100 devices per km$^2$ | 95% (Outdoors) |
| **Smart meters - sensor data, meter readings, individual device consumption (mMTC)** | 1,600 B per smart meter per day i.e. 200 B messages, 8 messages per day | 30k per km$^2$<br>100% uptake assumed from 2020 so no growth over time. | 99% (Indoors) |
| **Smart grid sensor data and actuator commands (mMTC)** | 60 kB per smart grid neighbour area network (NAN) gateway based on 20 B commands, 10 messages per day per smart meter device being controlled. | 1.3 smart grid neighbour area network gateways per km$^2$ in 2020 growing to 25.6 per km$^2$ by 2030 based on smart grid uptake in revenue forecasts (each controlling 300 smart meter devices). | 95% (Outdoors) |
| **Logistics sensor data for tracking goods (mMTC)** | 4 MB per day per equipped vehicle based on 200 B messages, 100 messages per day (i.e. updates every approx. 15 mins) per sensor. | On average 9 smart logistics vehicles per km$^2$ in 2020 growing to 58 by 2030 i.e. a 21% CAGR. Each vehicle assumed to have 200 tracked items so sensor density growing from 1,800 to 11,600. | 95% (vehicles, outdoor) |

# 10 Appendix B – Further detail on baseline traffic forecast assumptions

This appendix provides further detail on the baseline traffic forecasts assumed for our central London study area for the services outlined in the previous appendix.

## 10.1 eMBB for consumer portable devices baseline case

The medium traffic forecast or baseline volume of eMBB traffic to be served by mobile networks in the study area across all 3 evaluation cases is taken from Cisco's Visual Networking Index (VNI) [Cis16]. For 2017 to 2020, the Cisco VNI mobile traffic volumes forecast is used directly (with an average traffic volume growth of 48% Compound Annual Growth Rate (CAGR) over the 5 year period provided of 2015 to 2020) to dimension the starting network at 2020 (see Section 2.4 for network dimensioning rules). Beyond 2020, growth of 30% CAGR is used in line with D3.2 [5GN-D32] and the trend of a reducing growth CAGR over time observed from the Cisco VNI traffic volumes given up to 2020. This gives the eMBB traffic forecast per head of population per month for the UK as shown in Figure 2-5.

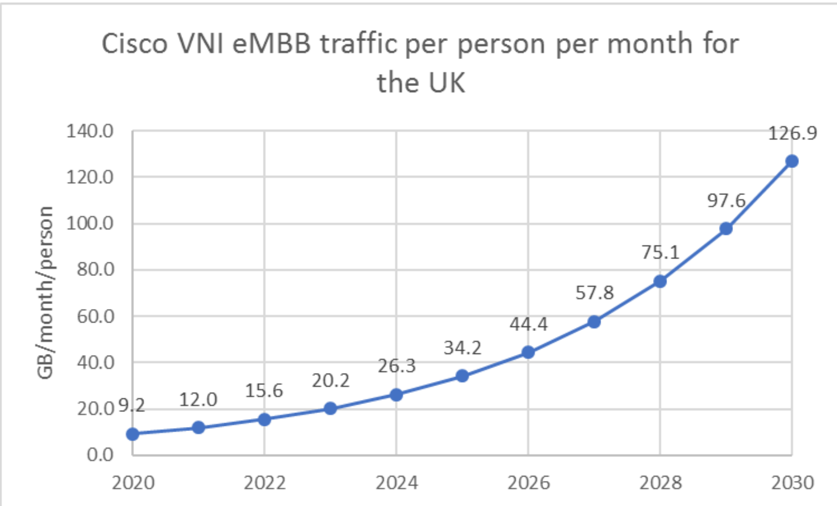



**Figure 10-1: eMBB traffic forecast per head of population for the UK per month based on Cisco VNI**

The following additional factors are then taken into account to translate this UK eMBB traffic volume to an outdoor busy hour eMBB traffic density for the study area:

- The residential population density of the study area vs. the mean residential population density of the UK based on Census 2011 data.
- An uplift factor of 3.78 between the residential population and the day time working population in the study area to allow for commuters [Tel11].
- A temporal distribution of demand and the ratio of indoor to outdoor demand over the different times of the day based on (as shown in Figure 10-2) the product of:
    - The ITU's profile of consumption of services for different hours of the day [M.2370-0].
    - Traffic volumes in the UK at different times of the day as a proxy to the temporal distribution of commuting times over the different hours of the day [Dot14].

  This highlights the busy hour for the outdoor network (i.e. peak commuting time) rather than the busy hour for both indoor and outdoor mobile demand across the day.

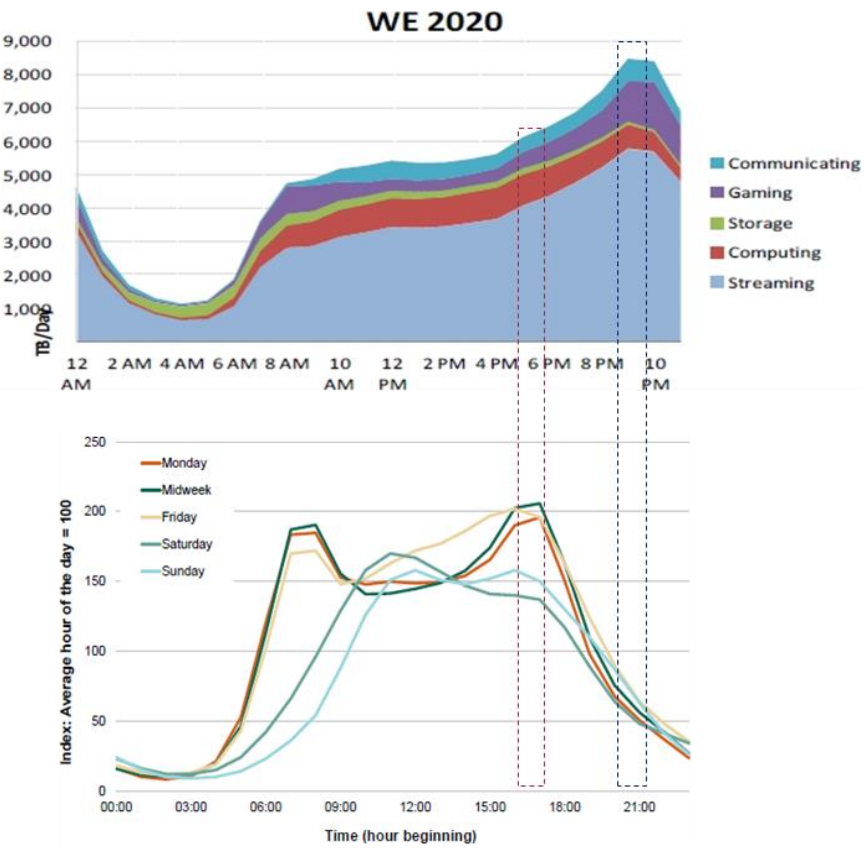



**Figure 10-2: Distribution of demand in Western Europe (WE) for different services over different hours of the day from ITU [M.2370-0] (upper figure) and relative vehicle volumes in the UK [Dot14] where an index of 100 represents the average vehicle use (lower figure).**

This results in the busy hour outdoor eMBB traffic density forecast across all service providers shown in Figure 10-3. Within this outdoor busy hour, due to combining the traffic from multiple users, there will be peaks in demand within this busy hour relative to the average demand density within this busy hour. Based on input from partners in the 5G NORMA consortium, we assume a cell is at maximum capacity once the average busy hour physical resource block (PRB) utilisation reaches 65% to allow for these peaks within the busy hour and to limit interference between cells.

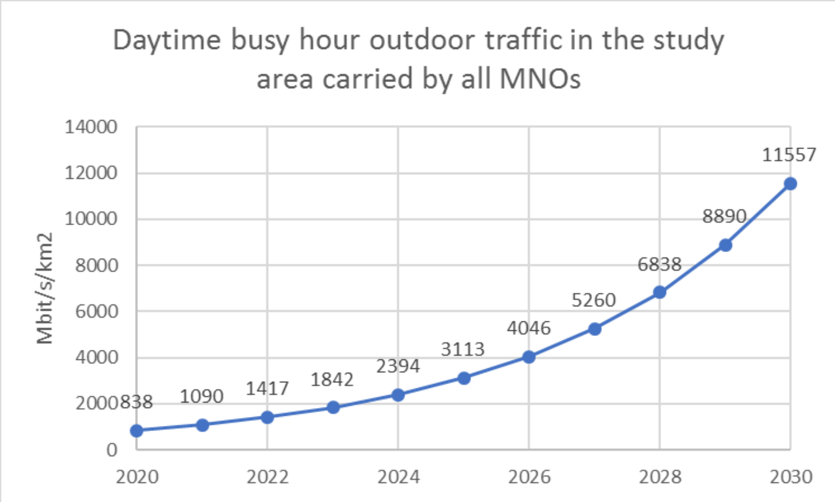



**Figure 10-3: Daytime busy hour outdoor eMBB traffic density forecast across all service providers for the study area**

## 10.2 Vehicle to infrastructure traffic forecast assumptions

As described in Section 0, within Evaluation Case 3 we consider three categories of services within vehicle to infrastructure services:

- Infotainment
- Assisted driving services
- Semi-automated driving services

In the absence of existing traffic forecasts for these services for the UK we have applied a bottom up approach to deriving traffic forecasts for each of these services. All V2X traffic is spatially distributed along the roads in the study area and temporally distributed over the 24 hours of the day in line with variations in vehicle volumes over the different times of day as used in the previous section for outdoor eMBB traffic i.e. it is higher during the commuting hours in the morning (6am to 9am) and evening (4pm and 7pm). There is also a uniform distribution of the traffic volume across vehicles, i.e. there are no vehicles that request more data than any other. The UL traffic volume is not modelled.

### 10.2.1 Infotainment traffic assumptions

Our forecasts of infotainment traffic volumes between 2020 and 2030 are based on combining:

- The average rate of infotainment data consumed per vehicle equipped for infotainment services in the study area which is based on:
  - A typical data rate of 18Mbps to support 4K streaming per active infotainment user (who must be a passenger rather than a driver)
  - An average number of passengers per vehicle of 0.62 [Tfl12]
  - An assumed activity rate of infotainment usage amongst passengers of 25% (based on input from 5G NORMA partners).
- The average density of vehicles in the central London study area based on:
  - Vehicle kilometres per year statistics for different road types for London [Tfl12b]
  - Lengths of different road types in London [Tfl12b]
  - The average speed in central London [Evs16]
- Uptake of infotainment services as described in Section 4.2.1.1.

### 10.2.2 Assisted and semi-automated driving traffic forecasts

Our forecasts of assisted driving and semi-automated driving traffic volumes between 2020 and 2030 are based on combining:

- The average rate of data consumed per vehicle equipped for with assisted and semi-automated driving services in the study area which is based on case 5.10 from 3GPPs release 15 vehicular use cases which describes communications between a UE and roadside unit to support information sharing for limited automated driving with typical message sizes of 6,000 B exchanged at rates of 10 messages per second [22.886].
- The average density of active vehicles on the roads in the central London study area based on:
    - Vehicle kilometres per year statistics for different road types for London [Tfl12b]
    - Lengths of different road types in London [Tfl12b]
    - The average speed in central London [Evs16]
- Uptake of assisted driving and semi-automated driving services as described in Section 4.2.1.1.

## 10.3 Smart meter and smart grid traffic forecast assumptions

Our forecasts of smart meter and smart grid traffic volumes between 2020 and 2030 are based on combining:

- The average rate of data consumed per smart meter and smart grid device based on message sizes and frequency of messages from GSMA of 200 B messages sent at a rate of 8 per day for smart meters and 10 B messages sent at 10 per day for smart grids [Gsm16].
- Assuming 3 smart meter devices per residential or business premise in line with IEEE [Iee11].
- Uptake of smart meter and smart grid services as described in Section 4.3.1.

There is a uniform distribution of the traffic volume across smart meters, i.e. there are no smart meters that request more data than any other. Figure 10-4 shows the assumed temporal distribution of smart meter traffic. The traffic is predominantly at hours of the day which are quiet for eMBB.

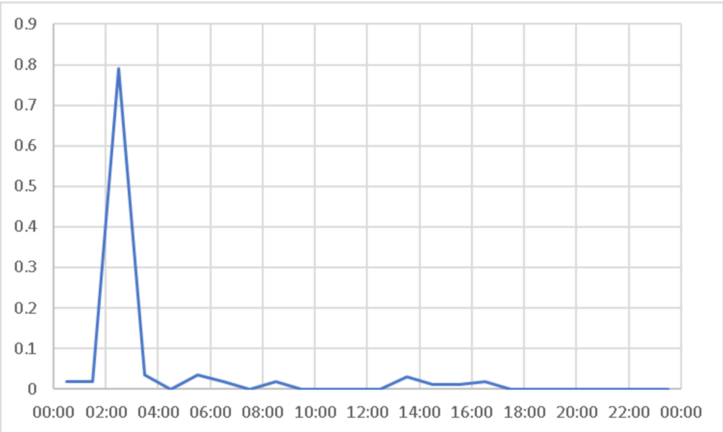



**Figure 10-4: Probability density function of assumed smart meter traffic distribution across the daytime [Sha+12]**

## 10.4 Smart city forecast assumptions

Our forecasts of traffic generated from roadside sensors in our smart city scenario between 2020 and 2030 are based on combining:

- The average rate of data consumed per roadside sensor based on message sizes of 1 B and frequency of messages of 1443 per day (i.e. one per minute) from IEEE [Iee11].
- Volumes traffic signals and road signs in the central London area [Itv15, Dft12].
- Uptake of smart city services as described in Section 4.3.1.

## 10.5 Logistics forecast assumptions

Our forecasts of traffic generated from vehicles availing of wireless logistics tracking services between 2020 and 2030 are based on combining:

- Assuming a message size of 200 B (i.e. the same as a smart meter device) with a message sent every 15 minutes.
- 200 tracked items assumed per vehicle [Bbc16].
- The average density of commercial vehicles in the central London study area based on:
    - Vehicle kilometres per year for different road types statistics for London [Tfl12b]
    - Lengths of different road types in London [Tfl12b]
    - The average speed in central London [Evs16]
- Uptake of logistics services as described in Section 4.3.1.

# 11 Appendix C – additional detail on cost modelling assumptions

Key assumptions on inputs to the cost model used in this analysis have already been described in Deliverable D2.2 [5GN-D22]. This appendix clarifies the areas where these assumptions have evolved since D2.2.

## 11.1 Spectrum available over time

The following spectrum availability over time is assumed from 2020 to 2030. Note that the economic model does not include modelling the mmWave bands in the “high unpaired” category as this implies highly localised small cells to serve demand hotspots.

Table 11-1 is based on spectrum availability proposed in D3.2 but updated to allow a slightly earlier release of medium band spectrum for small cells in 2023 to avoid unnecessary densification of the network which becomes poorly utilised in later years when additional spectrum is released. Note operation in unpaired bands is assumed to be with Time Division Duplex (TDD) with a DL/UL ratio according to LTE configuration 5.

Not all sites in the study area automatically upgrade to use all of the frequency bands and bandwidth outline here over the time frame of the study period. Rather the number of carriers on a site are only upgraded as needed over time in line with supporting the growing demand local to that site.

**Table 11-1: Bandwidth available per spectrum band and site type over time**

| Year | 2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 | 2029 | 2030 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Sub-1GHz paired (Macrocell) (DL bandwidth available)** | 15 | 15 | 15 | 25 | 25 | 25 | 25 | 25 | 25 | 25 | 25 |
| **Low paired (Macrocell) (DL bandwidth available)** | 60 | 60 | 60 | 60 | 60 | 60 | 60 | 60 | 60 | 60 | 60 |
| **Medium unpaired (Macrocell) (DL and UL bandwidth available)** | | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 20 |
| **Low unpaired (SC) (DL and UL bandwidth available)** | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 20 |
| **Medium unpaired (SC) (DL and UL bandwidth available)** | | | | 20 | 40 | 40 | 40 | 40 | 40 | 40 | 40 |
| **High unpaired (SC) (DL and UL bandwidth available)** | | | | | | 100 | 100 | 100 | 100 | 100 | 100 |

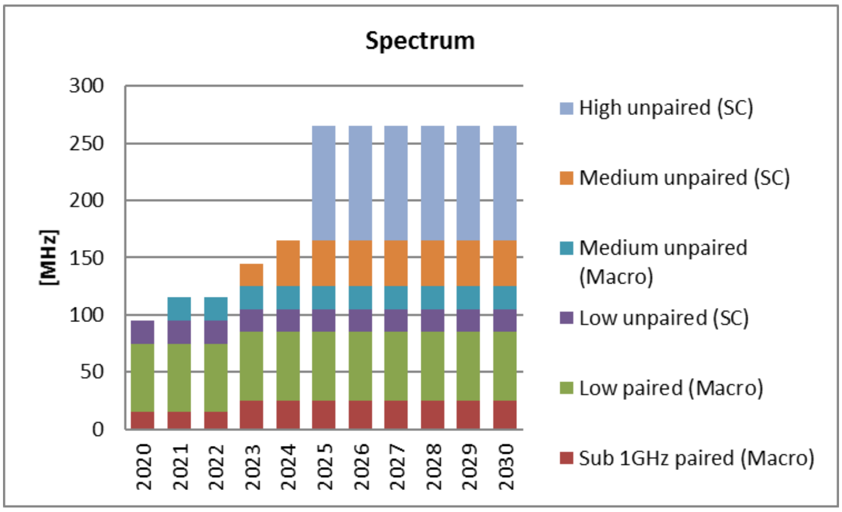



**Figure 11-1: Bandwidth available per spectrum band and site type over time**

## 11.2 Admission control

The 5G NORMA cost model assesses the demand in the study area in a given year and maps this demand to the existing sites in the area. The demand is "permitted" to be served by a particular antenna site type, site chain and/or frequency band depending on its:

- Latency requirements
- Application data rate
- Velocity of the user

Both site chain configurations 2 and 3 (described in Deliverable D2.2 [5GN-D22]) are considered low latency supporting in the order of 2ms latency requirements for services (due to localised core network functions being located at either the antenna site or edge cloud site combined with low latency dark fibre transmission). The traditional D-RAN configuration is considered higher latency in the order of 10ms latency requirements for services.

Each service has an associated application data rate where higher data rate services are directed towards small cells rather than macrocells.

The velocity of a user impacts the antenna site type which can serve demand from that user as follows in Table 11-2.

**Table 11-2: Mapping of user velocity to antenna site power amplifier classes**

| Power amplifier class of the antenna site | Maximum supported velocity (km/h) |
|---|---|
| **Macrocell** | 250 |
| **Small cell 5 W** | 50 |
| **Small cell 250 mW** | 5 |

If with the existing network at the start of a year there is unserved demand the cost model then upgrades existing sites and/or adds new sites until all demand is served.

When adding new sites the macrocell layer can be densified up to a minimum ISD of 250m [Nok16]. For small cells we assume a minimum ISD of 65m [Nok16] with a maximum of 5 small cells per macrocell sector and assuming 3 sector macrocells.

**Table 11-3 – Minimum ISD permitted when placing new sites**

| Site type | Low frequency band | Medium frequency band | High frequency band | Rationale |
|---|---|---|---|---|
| **Macrocell** | 250m | 250m | 250m | Nokia white paper [Nok16] |
| **Small cells** | 65m | 65m | 65m | This aligns with a maximum of 5 small cells per sector of a 3 sector macrocell if the macrocell has the minimum ISD of 250m [Nok16]. |

## 11.3 Spectrum efficiency

As per Deliverable D2.2 [5GN-D22], the WP2 cost model represents spectrum efficiency as a function of time, the service to be supported, the MIMO configuration and the deployment. Hence, we can approximate the achievable Spectrum Efficiency (in bits/s/Hz) as:

$$SE(t, service, MIMO, deployment) = CSH * OverheadGain * MIMOFactor * NetworkLoadingFactor * \ ServiceFactor * FrequencyFactor * RealTraffic * CellGeometryFactor * JointProcessingEfficiencyFactor,$$

and the user throughput (in Mbit/s) as:

$$T'put\ (t, service, MIMO, deployment, Bandwidth) = Bandwidth * SE,$$

where the parametric dependence of the parameters has not been shown to simplify the notation.

The factors in the above equation align to.

- CSH: The ability of communication waveforms to approach the Shannon bound, i.e. achievable raw spectrum efficiency prior to the factors below being applied. We assume a baseline spectrum efficiency for 2x2 FDD SU-MIMO here of 2.23 bit/s/Hz as per Deliverable D2.2
- OverheadGain: Reductions in overheads via more efficient waveforms or control traffic reductions. Currently this reflects FBMC improvements estimated at x 1.13.
- MIMOFactor: Gains via different orders of MIMO. See tables below for assumed MIMOFactors per MIMO configuration.
- NetworkLoadingFactor: In practice, base stations and realisable schedulers do not operate at 100% utilisation. When assessing coverage we assume 85% loading. When assessing capacity of a cell we assume, in line with feedback from the consortium, that once PRB utilisation reaches 65% the quality of service of users in the cell is degraded to the extent that upgrading the site to support more antennas or extra spectrum or building a new site to ease the capacity bottleneck should be considered.
- ServiceFactor: Changes in spectrum efficiency for different services due to low latency performance or smaller packet sizes and hence higher overheads.
- FrequencyFactor: Changes in spectrum efficiency with frequency band. Assumed to be 1 across all frequency bands in results presented.
- RealTraffic: Discounting factor to allow for reductions in SE between simulated full buffer traffic which the baseline SE values use compared with a more realistic traffic mix. We assume 0.65.
- CellGeometryFactor: This is a value to indicate cell geometry efficiency gain compared to traditional urban macrocell. Currently aligned to x 1.24.
- JointProcessingEfficiencyFactor: This is a value to indicate spectrum efficiency gain resulting from joint processing (e.g. for interference cancellation) resulting from joint processing of signals from multiple antenna sites. This is set to 1 in our the results presented in this report.

**Table 11-4: Mean SE per cell for SU MIMO FDD operation**

| | | Rx antennas | | | Comments |
|---|---|---|---|---|---|
| | | 2 | 4 | 8 | |
| Tx antennas | 1 | Rx diversity | Rx diversity | Rx diversity | Rx diversity |
| | 2 | 1.00 | Rx diversity | Rx diversity | As per D2.2 |
| | 4 | 1.13 | 1.53 | Rx diversity | As per D2.2 |
| | 32 | 2.37 | N/A | N/A | Updated from D2.2 to reflect further review within 5G NORMA WP2 |
| | 64 | 2.48 | 3.24 | N/A | Updated from D2.2 to reflect further review within 5G NORMA WP2 |

**Table 11-5: Mean SE per cell for SU MIMO TDD operation**

| | | Rx antennas | | | Comments |
|---|---|---|---|---|---|
| | | 2 | 4 | 8 | |
| Tx antennas | 1 | Rx diversity | Rx diversity | Rx diversity | Rx diversity |
| | 2 | 1.10 | Rx diversity | Rx diversity | As per D2.2 |
| | 4 | 1.25 | 1.68 | Rx diversity | As per D2.2 |
| | 32 | 2.60 | N/A | N/A | Updated from D2.2 to reflect further review within 5G NORMA WP2 |
| | 64 | 2.73 | 3.57 | N/A | Updated from D2.2 to reflect further review within 5G NORMA WP2 |

**Table 11-6: Mean SE per cell for MU MIMO FDD operation**

| | | Rx antennas | | | Comments |
|---|---|---|---|---|---|
| | | 2 | 4 | 8 | |
| Tx antennas | 1 | Rx diversity | Rx diversity | Rx diversity | Rx diversity |
| | 2 | 1.17 | Rx diversity | Rx diversity | As per D2.2 |
| | 4 | 1.54 | 2.10 | Rx diversity | As per D2.2 |
| | 32 | 2.78 | N/A | N/A | Updated from D2.2 to reflect further review within 5G NORMA WP2 |
| | 64 | 2.91 | 3.81 | N/A | Updated from D2.2 to reflect further review within 5G NORMA WP2 |

**Table 11-7: Mean SE per cell for MU MIMO TDD operation**

| | | Rx antennas | | | Comments |
|---|---|---|---|---|---|
| | | 2 | 4 | 8 | |
| Tx antennas | 1 | Rx diversity | Rx diversity | Rx diversity | Rx diversity |
| | 2 | 1.29 | Rx diversity | Rx diversity | As per D2.2 |
| | 4 | 1.69 | 2.31 | Rx diversity | As per D2.2 |
| | 32 | 3.06 | N/A | N/A | Updated from D2.2 to reflect further review within 5G NORMA WP2 |
| | 64 | 3.20 | 4.19 | N/A | Updated from D2.2 to reflect further review within 5G NORMA WP2 |

## 11.4 Virtualisation dimensioning

Previously in Deliverable D2.2 [5GN-D22], we proposed an approximate method of dimensioning D-RAN in terms of the number of equivalent 20MHz bandwidth 2x2 MIMO processing units that are deployed and used in the network. In this section, we present a method to identify the processing requirements for the L1-L3 processing required if general purpose processors are used.

[Nia15] derives a model for determining the computational burden of processing LTE-A (Release 10) with different bandwidths related to Physical Resource Blocks (PRB), Modulation and Coding Schemes (MCS) and virtualisation Operating System and architecture for a SISO system. [BC12] also presents a breakdown for the cloud processing and the statistical multiplexing in 'real systems'. This section reviews the findings of these papers and extrapolates these into the virtualisation dimensioning method used within the cost model to determine the number of Commercial Off the Shelf (COTS) cloud servers required for a given set of bandwidths and antenna configurations to be processed from a number of antenna sites.

### 11.4.1 Processing requirements for a 20MHz SISO channel

Based on the R10 LTE frame structure, assuming a fronthaul delay of 150us, 3ms are available to process the uplink and downlink to satisfy HARQ delay constraints. These time delays are likely to reduce in future releases, but these are anticipated to reduce in line with processing improvements, and so we use this approach as a proxy over the study period.

The dimensioning approach used is, therefore, to determine, for representative high performance processors, how many cores are required to process different parts of the receive chain in order to meet these HARQ time constraints.

The time required has been measured for 3 representative processors, and yielded broadly similar results. The time required to process the 1ms LTE R10 subframe, $T_{subframe}$, is broken down to 3 tasks which can be associated with different processing layers, and is a function of the number of PRBs used (in total and for each user), the MCS used by each user and the environment-dependent overhead to handle virtual machine processing, as shown:

$$T_{subframe}(PRB, MCS, ENV) = c(PRB) + p(PRB, ENV) + u_c(PRB) + u_s(PRB, MCS),$$

Where:

- Cell Processing, depends on the channel bandwidth (and is made up of two parts)
  - c(PRB) is cell (antenna site) related processing (includes cell-based processing – primarily IFFT/FFT)
  - p(PRB,ENV) is platform-specific load relative to physical platform assuming general purpose processors (GPP) (i.e. this is the overhead in running virtual

machines or containers instead of bare-metal processing on the device direct (for GPP))

- Remainder of the processing, dependent on the PRBs used by each user
  - $u_c$(PRB) is per-user processing (primarily scrambling, Downlink Control Information (DCI) coding, Physical Downlink Control Channel (PDCCH) coding)
- Dynamic Processing, specific to the user and dependent on MCS and PRBs
  - $u_s$(PRB, MCS) is user processing (dominated by (de)modulation and (de)coding)

The processing load for the user-based processing may use a different (smaller) number of PRBs than the cell-based processing. Since the loading varies more than linearly with MCS or PRB, adding up these parts per user will result in less load than processing the worst case full MCS across the full band. Hence any processing that is user-oriented (rather than cell oriented) would require less computation than the above with the maximum value used for PRB and MCS.

In practice a mix of different MCS values are used across the coverage area (NB this is likely to vary between site types, frequencies, etc). The authors of [BC12] argue that QAM distribution in LTE will be similar to WCDMA and used measurement data to determine DL QAM distribution as shown in Figure 11-2. The modulation scheme used is dominated by the lower SINR (signal-to-interference-plus-noise ratio) QPSK variant. Though up to 256-QAM will be used in future, it clearly will not be used very often and will not impact the average, though it will impact the peak processing burden. Some overhead must be allowed for this.

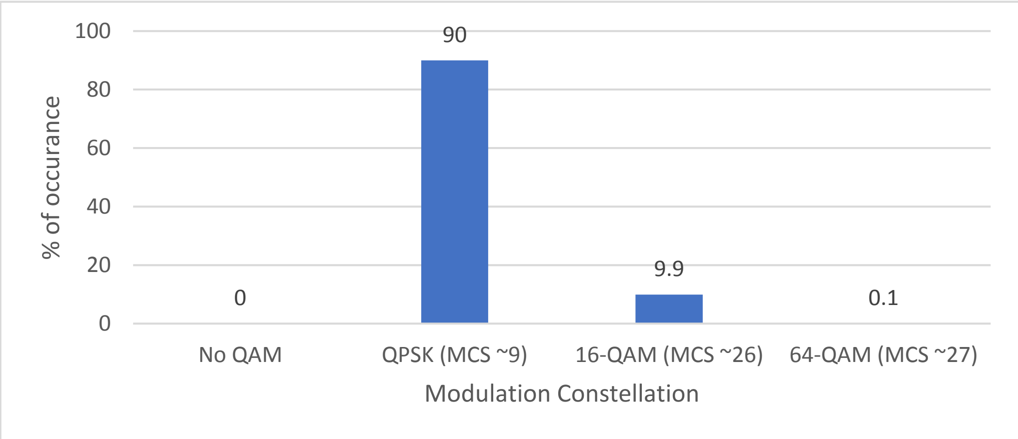



**Figure 11-2: Measured data of the occurrence of different constellations used in mobile network (most users are in low SINR conditions with lower order constellations). An equivalent MCS value is shown though MCS values also imply a particular coderate.**

We can therefore use the values from [Nia15] for the time taken to process 100 PRB at different MCS[24] values and the distribution of MCS values above to form a representative average of the processing time required. Using the KVM (virtual machine) approach, we find the processing times as shown below.

[24] The MCS index used here is for pre-R12 LTE variants, as used in [Nia15]. R12+ uses a different MCS table.

**Table 11-8: Processing times required for different processes using high-end x86 processor cores, and number of cores required (UL and DL) using Intel Sandy Bridge i7-3930K, running KVM, with a clock frequency of 3.2GHz, processing 100PRB SISO**

| Downlink | | MCS 27 | MCS 16 | MCS 9 | UNITS |
|---|---|---|---|---|---|
| | Cell/base processing | 133 | 133 | 133 | µs |
| | Remainder processing | 153 | 153 | 153 | µs |
| | Dynamic processing | 471 | 339 | 255 | µs |
| | DL_TOTAL | 757 | 625 | 541 | µs |
| **Uplink** | | MCS 27 | MCS 16 | MCS 9 | |
| | Cell/base processing | 135.4 | 135.4 | 135.4 | µs |
| | Remainder processing | 80 | 80 | 80 | µs |
| | Dynamic processing | 1328.1 | 867.2 | 573.9 | µs |
| | UL_TOTAL | 1543.5 | 1082.6 | 789.3 | # |
| **Cores Required** | Per MCS | 2.3 | 1.71 | 1.33 | # |
| | Weighted average | 1.37 | | | |

Hence, considering average conditions, on average 1.37 cores would be needed to process a 20MHz SISO channel, using the worst case of one user requiring all PRBs. This average number of cores could only be used if there is sufficient averaging that the peak loading could be handled on the few occasions necessary. A margin should be applied to this figure (see 11.4.3).

### 11.4.2 Impact of MIMO

For different MIMO orders (MxM, say) the same transmit / receive chain would need to be performed after channel deconvolution. Therefore, the computational burden should scale with M, for either the transmit or receive chain. If we assume that this deconvolution can be performed in dedicated hardware then the same amount of processing is required for each order of the MIMO deployment (we will term this for each MIMO_stream).

For MMIMO, a number of spatial beams can be formed and pre-processed at the antenna front end. Front-end beamforming will reduce the number of spatial beams to be processed (which will be significantly less than the number of elements). Currently it is not possible to use multiple MIMO streams in a spatial beam – but we assume that this may be possible in future – this has the impact of increasing the computation required. Hence, in general, the time needed to process MIMO is now increased by the product of the number of spatial beams and MIMO_streams to be processed. Therefore:

$$T'_{subframe}(PRB, MCS, ENV, SPATIALbeams, MIMOstreams) \\ = SPATIALbeams.MIMOstreams.T_{subframe}(PRB, MCS, ENV)$$

The number of assumed SPATIAL_BEAMS and MIMO_STREAMS for the different antenna configurations under consideration are shown in Table 11-9.

**Table 11-9: Assumed number of Spatial Beams and MIMO streams used for dimensioning the baseband processing**

| Basestation antennas | SPATIAL_BEAMS | N_MIMO_STREAMS | N_SPATIAL_BEAMS x N_MIMO_STREAMS |
|---|---|---|---|
| 2 | 1 | 2 | 2 |
| 4 | 1 | 4 | 4 |
| 32 | 8 | 1 | 8 |
| 64 | 8 | 1.5 (average) | 12 |

### 11.4.3 Aggregation margin

The figures for the number of required cores in 11.4.1 are based on (weighted) average values, or for a particular MCS value. In practice, with more aggregation, values closer to the average values for the user bandwidth being processed at an aggregation site will be needed; compared to the need for individual D-RAN sites needing to support up to the maximum capacity available. In practice, an additional margin above the average value will be needed.

We have used estimates of these additional margins as shown:

- Only the dynamic processing part needs to have a margin applied – since this is the part that varies with MCS. We increase the processing required above the average value by a factor of 1.5, if processing at an antenna site, or reduced to 1.25 if processed at the edge cloud site.
- It is noted that these factors of 1.5, or 1.25, are not sufficient to accommodate the processing if all users are using higher order constellations. Even on an individual site, this is highly unlikely.

## 11.5 CAPEX and OPEX cost assumptions

For CAPEX we assume equipment prices generally reduce (i.e. more capability delivered for similar or lower cost over time) whereas OPEX costs generally increase as they include an increasing labour cost element over time.

Note that across all site types, unless otherwise stated, we assume the following changes in costs with time:

- CAPEX cost inflation of -3%
- OPEX inflation of +3%

### 11.5.1 Antenna site CAPEX costs

The costs can be split into the following categories:

- CAPEX costs:
  - Site civil works and acquisition costs
  - Equipment costs including Antennas, Active equipment (including RF front ends and any baseband processing)
  - Transport costs[25]
- OPEX costs:
  - Operational costs – including per site overhead and per cabinet variable costs, and licensing and maintenance.

Many of these elements are common whether a D-RAN or C-RAN architecture is used.

#### 11.5.1.1 Site civil works and acquisition costs

The assumed site civil works and acquisition costs for 3 different site types is shown in Table 11-10. We assume that these costs stay constant over time i.e. unlike other CAPEX costs such as equipment site values, rents and structural build costs are unlikely to decrease over time.

[25] The transport costs consistent with the assumptions identified in [5GN-D22] capable of supporting the bandwidth requirements from [5GX-D21] will be used. In practice, in the study area, dark fibre will be favoured for all but the least busy sites.

**Table 11-10: Site civil works and acquisition CAPEX for a new antenna site**

| Cell type | Site civil works & acquisition | Source and comments |
|---|---|---|
| Macrocell<br>(3 sectors) | £ 46,200 | Based on industry experience of sites in central London. Corresponds to a medium cost value of a roof top site |
| Small cell<br>(2 sector small cell) | £ 4,800 | Based on Real Wireless Small Cell Forum business case for urban small cells |
| Picocell<br>(1 sector mmWave small cell) | £ 4,800 | Based on Real Wireless Small Cell Forum business case for urban small cells |

#### 11.5.1.2 Antennas and RF front ends

Our assumed costs for antennas and RF front ends are given on Table 11-11. The number of antenna panels required depends on:

- The maximum set of frequency bands supported by the site (keeping in mind that some antennas can cover multiple bands)
- The maximum MIMO configuration per frequency band supported by the site.

Equipment is not generally available that can support the functionality assumed – and so we have made some assumptions to derive reasonable costs. In line with [5GN-D32] and industry sources, we assume that multi band antennas are available for macrocell sites supporting the sub-1GHz and low frequency bands and incur no additional cost over a single band antenna. Each antenna column is cross polarised and so antenna ports start at 2 and increment in units of 2. As per [5GN-D32] we assume that an antenna panel contains two antenna columns and so the cost of antennas for a 4 antenna vs. 2 antenna site is not a doubling in cost as the same antenna panel can be used but just populated with a second antenna column. A scale factor of 1.5 has been used.

In line with [5GN-D32], specific separate antennas are required for each of the medium and high frequency bands with these supporting 32 or 64 antenna ports. We assume that as these massive MIMO arrays can be housed in a single panel their cost increment will not be as much as the x16 or x32 that their relative increase in the number of antennas from 2 or 4 antennas might suggest. Instead we assume that the cost of a 32 element antenna will be twice the cost of a 4 element antenna based on:

- There being an 8 times increase in the number of antenna elements
- The approximate doubling in frequency between the low and medium bands allowing x4 elements in the same area at the medium frequency as at the low frequency band.
- Therefore only x2 increase in cost is needed from 4 elements at low frequency to 32 elements at medium frequency

Other assumptions on antenna costs include:

- An additional feeder cost (based on fibre optic cables being used to connect the active antennas to the equipment cabinet), install and test and commission one-off CAPEX is incurred to install antennas on new sites.
- The same antenna costs are assumed for small cells (2 sector small cells at low and medium frequency bands) and picocells (single sector mmWave small cells) currently

RF front end costs are dimensioned based on the number of frequency bands, number of antennas per frequency band and bandwidth per frequency band supported. Our assumptions on the baseline RF front end cost for supporting 20MHz of bandwidth for each frequency band and supported antenna configuration is given on Table 11-11. The RF front end cost per frequency band with the supported antenna configuration in Table 11-11 therefore needs to be scaled based on the supported bandwidth in that frequency band relative to 20MHz. These RF front end costs are then summed across all supported frequency bands. For TDD, the total spectrum is used (i.e. 1x40MHz TDD is treated the same as 2x20 FDD).

| Site type | MIMO order | Antenna cost increment factor | Antenna cost | Feeder, install and test and commission costs per site | RF front end multiplier for each 20MHz of bandwidth supported per frequency band |
|---|---|---|---|---|---|
| Macrocell<br>(3 sectors) | 2 (sub-1GHz and low) | 1 | £ 1,600 (for 3 sectors) | £4,400 | £11.25k (for 3 sectors) |
| | 4 (sub-1GHz and low) | 1.5<br>(assumes panel re-use – extra antenna column only) | £2,400 (for 3 sectors) | £4,400 | X1.5 2 antennas case above |
| | 32 (medium and high frequency bands) | 2x 4 antennas at low frequency (Assumes x4 more elements in same area due to doubling of frequency and so only x2 times more elements needed) | £ 4,800 (for 3 sectors) | £4,400 | £24k (for 3 sectors)<br>(based on under £1k per antenna based on £3k 2x2 small cell units available at similar power levels including RF front end and baseband processing) |
| | 64 (medium and high frequency bands) | 2x 1.5 x 4 ants at low frequency (similar uplift in cost as 2x2 to 4x4) | £ 7,200 (for 3 sectors) | £4,400 | x1.5 32 antennas<br>(similar uplift in cost as 2x2 to 4x4) |
| Small cells<br>(2 sector small cells at low and medium frequency bands) | 2 (low and medium unpaired) | 1 | £250 for 2x2 MIMO base case (per sector) | £700 | Part of integrated active equipment |
| | 4 (low and medium unpaired) | 2 x small cell 2x2 | £500 for 4x4 MIMO (per sector) | £700 | Part of integrated active equipment |
| Picocell (single sector mmWave small cells) | 32 (mmWave unpaired high band) | 1 | 32x2 £250<br>(per sector) | £700 | Part of integrated active equipment |
| | 64 (mmWave unpaired high band) | 2 x picocell 32x2 | 64x4 £500 (per sector) | £700 | Part of integrated active equipment |

**Table 11-11: Antenna and RF front end CAPEX assumptions**

#### 11.5.1.3 Baseband processing

The D-RAN architecture performs the baseband processing at the antenna site. These are the costs assumed for a classical D-RAN deployment. Consistent with the method of scaling the processing for MIMO and additional bands identified in Section 11.4.2, the cost is based on the number of 2x2 MIMO streams and spatial beams that need to be processed. The CAPEX cost of the Baseband Units is set at £3750 for every 3 sectors of a 20MHz 2x2 MIMO channel, scaled by the number of MIMO streams and spatial beams deemed to be used at the site.

### 11.5.2 Antenna site OPEX costs

The assumed antenna site OPEX costs are shown in Table 11-12.

**Table 11-12: Antenna site OPEX costs**

| Power Amplifier Class | Sectors | Site Rental (£K) | Rates and Utilities (£K) | Vendor Services (£K) | Licensing and Maintainance (£K) | Comments |
|---|---|---|---|---|---|---|
| Macrocell | 3 | 20 | 10 | 3.2 – site chain config 1 and 3<br>1 for site chain config 2 (RRH site visits and maintenance) | 10% of Active Equipment – site chain config 1 and 3<br>10% of the RF front end costs for site chain config 2 (processing costs accounted at the edge cloud) | As per D2.2 but with central London uplift based on industry experience |
| Small cell (2 sector small cells at low and medium frequency bands) | 2 | 1 | 0.54 | 0 | 25% of Active Equipment | As per D2.2 but with central London uplift based on industry experience |
| Picocell (single sector mmWave small cells) | 1 | 1 | 0.54 | 0 | 25% of Active Equipment | As per D2.2 but with central London uplift based on industry experience |

We assume that the "rates and utilities" OPEX of an antenna site is fixed regardless of the antenna site configuration or if the site is used for C-RAN or D-RAN, i.e. landlords would be unlikely to offer a discount even if less equipment is deployed on site.

C-RAN sites would need less maintenance owing to reduced infrastructure and less active equipment being on-site. The rates and utilities has not been adjusted to account for additional equipment being deployed on site – this is a simplification since the costs involved at any one site for utilities are reasonably small. However, the electricity costs are fully costed at the edge cloud sites, which may result in a small favouring of D-RAN utility costs. All these costs are estimates and this difference is unlikely to be material.

### 11.5.3 Processor, server and edge cloud costs

#### 11.5.3.1 Processor costs trends

We base server/processor costs on the Xeon E5-26xx series – this is Intel's family that supports multi-processor, high performance server processor. These support up to 2 processors, but allows each direct access to I/O cards which would not be possible with the Ex-46xx families. This therefore seems to be a reasonable balance of price performance.

According to Intel's website the cost per core of the E5-26xx series for versions 1 to 4 has changed as shown in Figure 11-3.

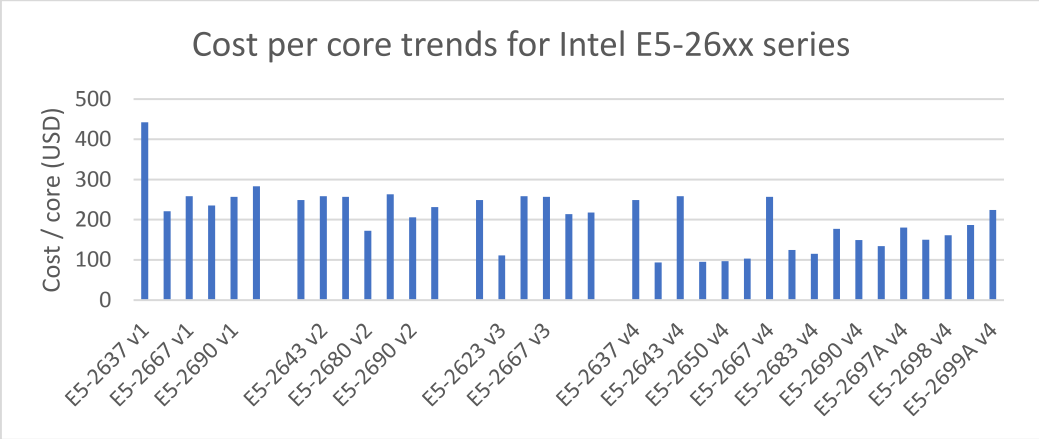



**Figure 11-3: Cost per core for Intel's E5-26xx family of processors for Version 1 (release Q1 2012) to Version 4 (released Q1 2016).**

From Figure 11-3 and Figure 11-4 it can be seen that there is a general downward trend in cost per processor – with a premium paid for the highest performing processors at initial release. Cache/core for the high performance processors has converged to a value of 2.5MB/core.

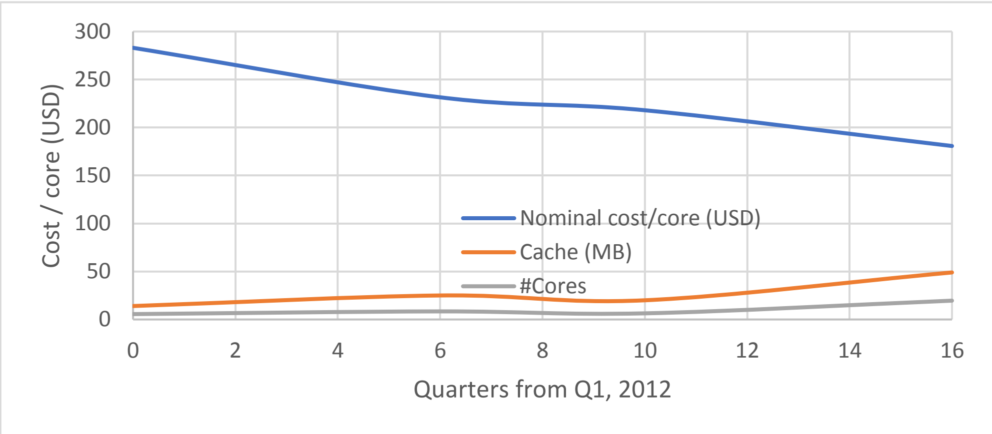



**Figure 11-4: Average values per version release from the initial version of the Xeon E5-26xx series (cost per core, cache/processor and number of cores per processor).**

However, tracking high end processors across the different versions it appears that high end core prices seem to hold their value after any initial price drop after introduction. Using 3 families of E5-26xx processor which have had processors in each of the different versions released, it can be seen that the price per processor appears to be reasonably stable after an initial cost reduction following introduction (see Figure 11-5). This appears to be contrary to the trend of ever reducing processor cost and improving processor performance and perhaps indicates that the high end processor market is not yet mature. For the sake of this study, we conservatively assume no price drop until there is more evidence of a viable price reduction metric.

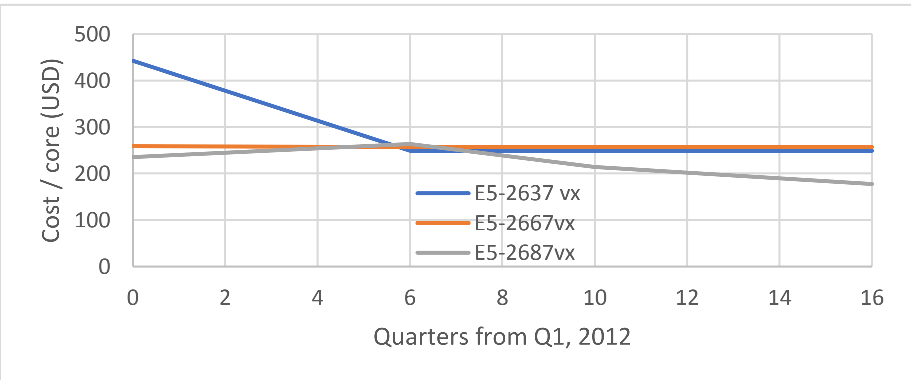



**Figure 11-5: Cost / core for 3 families of high performance CPUs across generations.**

#### 11.5.3.2 Server cost assumptions

The nominal cost per processor indicated on Intel's website is very similar to the retail cost from Broadberry[26] who configure and retail servers. However, we believe that a communications infrastructure provider would be able to secure significant discounts on these prices. We therefore apply a discount to the nominal values from Broadberry.

From the Broadberry site, we can configure a dual processor E5-2667 based server. Including memory, raid disc and dual port 16Gbit/s fibre channel host bus adaptor results in a 16 core server costing approximately £10K. It would require approximately 6 cores to process 4x4 MIMO 20MHz bandwidth (based on 1.37 cores required for a 20MHz SISO assumption from earlier) – and this would need approximately 5 Gbit/s Common Public Radio Interface (CPRI) [CPRI15] – so this server configuration is reasonable for the use envisaged in our analysis. This results in a nominal cost of an installed server of £625/core (including casing, power supply, networking, etc.). The server is 19" rack compatible with a 2U form factor.

It is assumed that the edge cloud facility can support tall 19" racks (up to 42U units are readily available). Allowing some space for cooling (10U), we can assume that 16 servers with the 2U form factor can be fitting into one 19" rack. Each server has a maximum power of 1100W – but we assume only 540W is needed (each processor is 135W).

We can summarise the key server and cabinet parameters as given in Table 11-13 below.

**Table 11-13: Baseline server configuration and cost**

| | Metric | Unit | Comment |
|---|---|---|---|
| **Server (nominal) cost** | 10,000 | £ | Based on CyberServe R2224WTTYSR v4 architecture, with 2 E5-2667 v4 processors (E5-2667 v4, 8 core, 3.2GHz, 25MB cache, 135W / processor), dual 10Mbps fibre ports, SATA raid disks. |
| **Assumed Discount on nominal cost** | 35 | % | Assume at least 35% cost savings on commercial individual rates (ie £6,500 cost per server) |
| **Server power consumption** | 540 | W | Server power supply capable of 1100W – but not fully loaded - Processor power 135W |
| **Server size** | 2 | U | Occupies 2U on standard racks. |
| **Core/cabinet** | 256 | # | Assumes 42U cabinet with 32U for 16 servers. |
| **Number of configuration 1 macrocells/cabinet** | 24 | # | Assumes 2x2 MIMO, 20MHz carriers, 3 sectors basestation which would each require approximately 10 cores per basestation based on the 1.37 cores per 20MHz MIMO stream assumption earlier, a margin x 1.25, x 2 for the MIMO order and a further factor x 3 for the sectors. |

#### 11.5.3.3 Edge Cloud site cost assumptions

Local loop unbundling has been regulated in many European countries and dominant fixed line operators are obliged to allow unbundled operators to deploy equipment in local exchanges. Since these exchanges are at convenient locations for fibre termination, power and rack space, we have used these LLU (Local Loop Unbundling) costs as a proxy for the cost of deploying equipment at edge cloud sites. Published data on these costs is available at [Ope15].

The costs can be split into the following categories:

- CAPEX costs:
    - Fixed costs to set up an installation at an edge cloud site

[26] http://www.broadberry.co.uk/xeon-e5v3-rackmount-servers/cyberserve-xe5-r2224wttysr

  - Fixed costs to set up a cabinet/rack in the edge cloud site
  - Fixed costs of deploying server equipment in a rack
- OPEX costs:
  - Operational costs – including per site overhead and per cabinet variable costs, and licensing and maintenance.

Note that edge cloud site OPEX costs are assumed to grow at a rate of 3% per annum in line with other OPEX items included in the cost model. However, our review of processor costs show that high end processors tend to hold their value over time. Additionally, our edge cloud CAPEX items are made up of a mix of equipment costs and labour to configure servers, install cabinets etc. While equipment costs may reduce labour costs will increase. We therefore assume no cost erosion for edge cloud site CAPEX items over time.

Based on the server characteristics we can identify the CAPEX and OPEX costs as shown in

Table 11-14 and Table 11-15.

**Table 11-14: Edge Cloud CAPEX costs**

| | Metric | Unit | Comment |
|---|---|---|---|
| **Fixed costs for initial set up pf an installation at edge cloud site** | 10,100 | £ | Based on estimates for base station hotel set-up costs, and LLU costs for metering and site visit. Costs include: power supply distribution boards, sockets, lighting, enclosure, overhead racking and cabling. |
| **Fixed costs to set up a cabinet/rack at the edge cloud site** | 21,400 | £ | Includes power distribution, Air Conditioning set-up, space set-up, AC distribution and cabinet. |
| **Fixed costs per server** | 6,500 | £ | Maximum of 16 servers per cabinet. Assumes 35% discount. This is equivalent to just under £490/installed core (for a fully equipped cabinet) |

**Table 11-15: Edge Cloud OPEX costs**

| | Metric | Unit | Comment |
|---|---|---|---|
| **Licensing and maintenance** | 10% | # | Assumed licensing and maintenance of 10% of the capex of the active equipment capex needed to process the sites feeding into each edge cloud. |
| **Transport** | 1150 | £ | This is assumed dark fibre costs – this could be an underestimate and would depend upon the capability to support all the fibres feeding into the site. Fibre communications modules are installed in each server. |
| **Standing charges / edge cloud** | 6,300 | £ | Security and working practices audit (assumed annual per site), and one site maintenance and update visit (per site)) |
| **Site rent and utilities/cabinet** | 6,600 | £ | This includes, rental and service charge (for a cabinet space, and working space), Standby Power / cabinet, Power connection (rental), Electricity use (of a fully stacked cabinet). Electricity use is the dominant cost. |

### 11.5.4 Site upgrade costs

Within the network cost model, infrastructure is assumed to have a limited useful life. Each year equipment can be added (new sites) or upgraded to accommodate demand or refreshed (when a site has reached the end of its useful life).

We assume the following equipment replacement or "refresh" frequency per site type:

- 10 years for macrocell antenna sites
- 5 years for smaller cell sites (small cells and picocells)

- 4 years for edge cloud servers

The C-RAN and D-RAN sites that are in place at the beginning of the study period are assumed to have been established at a random point in history – and will be replaced assuming random ‘birthdays. The ‘birthday’ of equipment procured during the study period is noted and replaced at a suitable time.

The site upgrade costs for site upgrade or refresh of an existing site, used in the model, are defined in Table 11-16, below.

**Table 11-16: Summary of costs incurred with site upgrades and refreshes**

| Upgrade type | Site type | One off CAPEX charge | On-going OPEX implications |
|---|---|---|---|
| **Increasing antenna count, adding a frequency band or "refreshing" a site** | Macrocell antenna site | Additional antenna (noting £3k in "other costs" for extra feeder but install cost included in £700 below), RF front end and baseband equipment cost for revised site configuration as per "new antenna site" equipment dimensioning earlier. For example, going from 2x2 to 4x4 incurs the cost of 2 new antennas (i.e. going from 2 to 4) plus £3k feeder cost, increase in RF front end cost of going from 2 to 4 antennas and extra baseband processing for additional bandwidth to be processed antenna site cost difference plus £3k feeder cost.<br>Note if site chain configuration 2 baseband equipment will be at edge site rather than the antenna site and so no baseband equipment CAPEX will be incurred at the antenna site.<br><br>£700 labour cost assumed based on 2 people for 1 day to install above equipment on rooftop macrocell site @ £350 per person per day (as at 2017) installation.<br><br>Check if existing site transport can handle increased bandwidth and if not upgrade as per transport upgrade option on this table. | Licensing and maintenance OPEX will increase as is 10% of active equipment.<br><br>Note rates and utilities assumed fixed regardless of macrocell antenna site configuration. |
| | Small cell and picocell antenna sites | Additional antenna and active equipment cost for revised site configuration as per "new antenna site" equipment dimensioning earlier.<br>£275 installation cost per small cell assuming:<br>- 4 small cells upgraded per day<br>- £400 per day for a cherry picker (as at 2017)<br>- £700 labour cost assumed per day based on 2 people required to install the unit @ £350 per person per day (as at 2017)<br><br>Check if existing site transport can handle increased bandwidth and if not upgrade as per transport upgrade option on this table. | Licensing and maintenance OPEX will increase as is 10% of active equipment.<br><br>Note rates and utilities assumed fixed regardless of macrocell antenna site configuration. |

| Upgrade type | Site type | One off CAPEX charge | On-going OPEX implications |
|---|---|---|---|
| | Edge cloud site<br>(Site chain configuration 2 only) | Additional edge node processing CAPEX for increased site capacity as per edge node equipment dimensioning described for new sites earlier.<br><br>£87.50 labour cost assumed based only 1 person required to add server blades to an existing rack and assuming able to visit 4 edge cloud sites per day.<br><br>Check if existing site transport can handle increased bandwidth and if not upgrade as per transport upgrade option on this table. | Licensing and maintenance OPEX will increase as is 10% of active equipment of macrocells and 25% of active equipment costs of small cells being aggregated. |
| | Central cloud site | None – assume central cloud capacity upgrades are part of routine maintenance | None |
| **Increasing supported bandwidth to an existing frequency band on an antenna site** | Macrocell antenna site | Additional RF front end and baseband equipment cost for revised site configuration as per "new antenna site" equipment dimensioning earlier. Note if site chain configuration 2 baseband equipment will be at edge site rather than the antenna site and so no baseband equipment CAPEX will be incurred at the antenna site.<br><br>Labour as per macrocell antenna site case above.<br><br>Check if existing site transport can handle increased bandwidth and if not upgrade as per transport upgrade option on this table. | As per macrocell antenna site case above |
| | Small cell and picocell antenna site | New active equipment cost for revised site configuration as per "new antenna site" equipment dimensioning earlier<br><br>Labour as per small cell antenna site case above.<br><br>Check if existing site transport can handle increased bandwidth and if not upgrade as per transport upgrade option on this table. | As per small cell antenna site case above. |
| | Edge cloud site | Equipment and labour as per edge cloud site case above. | As per edge cloud site case above. |

| Upgrade type | Site type | One off CAPEX charge | On-going OPEX implications |
|---|---|---|---|
| | | Check if existing site transport can handle increased bandwidth and if not upgrade as per transport upgrade option on this table. | |
| | Central cloud site | As per central cloud site case above. | As per central cloud site case above. |
| **Upgrade site transport type from managed fibre to dark fibre (i.e. when site transport bandwidth requirement goes beyond entry level 1Gps product to 10 Gbit/s)** | Macrocell antenna site<br>Small cell and picocell antenna site<br>Edge cloud site<br>Central cloud site | CAPEX incurred as per installing dark fibre transport to a new site described earlier. | OPEX incurred as per installing dark fibre transport to a new site described earlier. |
| **Upgrade dark fibre site transport bandwidth** | Macrocell antenna site<br>Small cell and picocell antenna site<br>Edge cloud site<br>Central cloud site | Assume spare fibres available so no dig cost incurred when increasing dark fibre bandwidth.<br><br>CAPEX for new modems required to provide higher bandwidth assumed to be per link (i.e. a pair of modems):<br>- £2,000 for 10 Gbit/s (as at 2015)<br>- £4,500 for 100 Gbit/s (as at 2015)<br>Note no CAPEX installation cost incurred as assume install is part of annual maintenance already part of transport OPEX. | OPEX incurred as per installing dark fibre transport to a new site described earlier |
| **Conversion from D-RAN to C-RAN** | Macrocell antenna site<br>Small cell and picocell antenna site<br>Edge cloud site<br>Central cloud site | No new CAPEX for RAN equipment at antenna site as using existing antennas and RF front end. Only CAPEX at antenna site should be:<br>• £250 CAPEX charge per sector for getting power from in building equipment room back up to the rooftop RRH in converting from D-RAN to C-RAN<br>• Transport CAPEX inline upgrade costs given above for the required type of site transmission upgrade needed. The required transmission upgrade needed will depend on the original site transport in the D-RAN network and the revised requirement under C-RAN. | OPEX of macrocell antenna sites will reduce to site chain configuration 2 values with potential exception of antenna site transmission OPEX which will change in line with the site transmission upgrade needed. Extra OPEX now incurred for new edge cloud sites as described in Section 11.5.3. |

| Upgrade type | Site type | One off CAPEX charge | On-going OPEX implications |
| --- | --- | --- | --- |
| | | Small cell antenna sites assumed D-RAN and so no conversion to C-RAN costs.<br><br>New edge cloud sites will be needed so CAPEX as per setting up a new edge cloud site will be incurred. | |