# Denser networks for the Future Internet, the CROWD approach

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**Abstract.** This paper presents the key ideas behind the ICT CROWD[1] (Connectivity management for eneRgy Optimised Wireless Dense networks) project, funded by the European Commission. The project moves from the observation that wireless traffic demand is currently growing exponentially. This growing demand can only be satisfied by increasing the density of points of access and combining different wireless technologies. Mobile network operators have already started to push for denser, heterogeneous deployments; however, current technology needs to steer towards efficiency, to avoid unsustainable energy consumption and network performance implosion due to interference. In this context, CROWD promotes a paradigm shift in the future wireless Internet architecture, towards global network cooperation, dynamic network functionality configuration and fine, on demand, capacity tuning. CROWD pursues four key goals: (*i*) bringing density-proportional capacity where it is needed, (*ii*) optimising MAC mechanisms operating in very dense deployments by explicitly accounting for density as a resource rather than as an impediment, (*iii*) enabling traffic-proportional energy consumption, and (*iv*) guaranteeing mobile user's quality of experience by designing smarter connectivity management solutions.

## 1 Introduction

Wireless data communication is a constituent part of everyday life for hundreds of millions of people. The number of wireless users is rapidly increasing, the offered load doubling every year, thus yielding a 1000x growth in the next ten years. Additionally, expecting high-quality services and high data rates is becoming normal rather than exceptional. Therefore, considering a density population of 5000 people/Km$^2$, which is typical of large European cities like London,

[1] The CROWD project is an accepted project under FP7 and will start on 01/01/2013.

Madrid, or Paris, and accounting for 20% of the population being mobile data users, each demanding 1 Mbps, would lead to a demand of 1 Gbps/Km$^2$, which can be hardly provided by current wireless infrastructures. The figure grows further if we consider that the per-user demand is expected to increase ten-fold in the next 5 years.[2]

The solution to cope with this growing traffic demand necessarily entails using more points of access, by increasing their density (dense network deployments) and/or by using different wireless technologies (heterogeneous deployments).[3] Following this trend, operators have already started to push for denser deployments,[4] building micro-, pico- and femto-cells, and installing Wi-Fi hotspots in public areas to inject capacity where the data traffic demand is particularly high.

These efforts notwithstanding, we argue that increasing the number of points of access alone would not remove capacity and performance bottlenecks. In fact, dense deployments are not necessarily synonymous with higher capacity. The case of smart meters is a key example. It has been recently noticed that the diffusion of meters for gas and electricity, endowed with wireless transmitters using the 2.4 GHz ISM band, is generating erratic behaviour in Wi-Fi home devices in USA.[5] Furthermore, having a large number of deployed access points also influences the energy cost, especially for the network operator. In particular, today's access points and base stations running at zero-load consume almost as much energy as when running at full capacity. As a result, wireless dense networking can potentially lead to wireless chaos and huge energy waste.

Currently available solutions for optimising the operation of mobile and wireless networks, including recent advances in PHY-layer techniques like interference cancellation, are not sufficient for heterogeneous and dense deployments like the ones existing or under deployment. Indeed, while PHY approaches have been widely investigated to deal with very dense networks, they take a restricted PHY perspective; they do not consider that higher-layer mechanisms are required to globally optimise per-flow performance by orchestrating mechanisms at different layers and subsystems. Furthermore PHY-based optimisations do not scale with network density and cannot be easily extended to the case of heterogeneous wireless technologies. In fact, the complexity required to optimise multiple nodes in real time becomes prohibitively high when nodes use heterogeneous PHYs.

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[2] Cisco Visual Networking Index: Global Mobile Data Traffic Forecast Update, 2010-2015.

[3] Noticeably, while PHY-layer improvements have produced only a 5x performance improvement over the past decades, and spectrum management has introduced a 25x gain, network capacity has been increased by a factor 1600 by reducing per-cell coverage as explained by Cooper's Law (see Martin Cooper at Arraycomm, `http://www.arraycomm.com/technology/coopers-law`)

[4] WLAN Scalability Test Report, Joint Universities Computer Centre, Sponsored by ARUBA Networks. `http://www.arubanetworks.com/pdf/technology/whitepapers/wp_HiEd_JUCC_Rpt.pdf`

[5] Smart meters blamed for Wi-Fi router traffic jam, CNET News. `http://news.cnet.com/8301-11128_3-57328603-54/smart-meters-blamed-for-wi-fi-router-traffic-jam/`

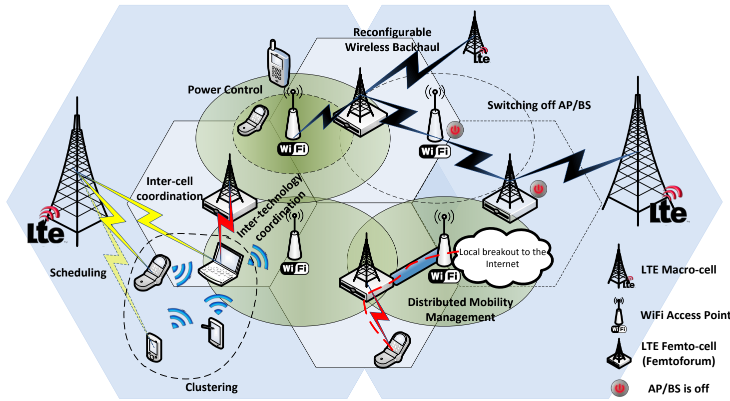


**Fig. 1.** Crowd Framework

In the above context, we aim at developing a novel networking framework that can satisfy future traffic demands by leveraging density and heterogeneity. Fig. 1 presents CROWD's vision of what are the required key technologies to support a very dense and heterogeneous wireless deployment. The depicted framework comprises small and large LTE cells, overlapping with each other and with Wi-Fi hotspots. As such, the framework accounts for managed (LTE-like) and unmanaged (Wi-Fi-like) deployments in the same geographical areas. Altogether, cells and hotspots form the CROWD access network. The other key component of the CROWD framework depicted in the figure is the wireless backhaul; with a very high density, it is unlikely that all the points of access can be reached with wired connections, due to installation costs and practical limitations, and hence some of them will have to rely on a wireless backhaul connection.

In a nutshell, the CROWD project aims at building high-capacity energy and resource-efficient wireless dense networks. To do so, the project will devise novel mechanisms for connectivity management, energy-efficient operation, scheduling and random access MAC enhancements, and dynamic backhaul optimisation. These mechanisms will be mutually integrated with each other and span across cell boundaries, technology boundaries, and access/backhaul network boundaries, jointly optimising the performance metrics of these subsystems.

The rest of the paper is structured as follows; Section 2 presents the key challenges to be addressed in order to take advantage of the increasing density on the RAN. Section 3 shows the current state of research regarding very dense deployments. The approach taken by the CROWD project in order to address the challenges identified in Section 2 is presented in Section 4. We conclude with Section 5.

## 2 Key Challenges

We next describe the key challenges that have been identified to realise a truly and effective very dense RAN. To do this, we provide in the following a general description of the challenges and then we identify for each one the different algorithms that contribute to its development.

### 2.1 Density-proportional capacity

In an ideal setting, the capacity increase would be proportional to the increase in the density of points of access. Therefore, a key challenge is to approach this ideal setting as much as possible by providing a capacity increase approximately proportional to the density increase. With small cells, enhancing LTE and WLAN MAC protocols can increase per-cell capacity to a few tens of Gbps. However, uncoordinated neighbour cells cannot simultaneously operate at full capacity due to interference in the limited available radio spectrum. In order to overcome these impairments and achieve a network throughput approximately proportional to the density of the deployed points of access, we propose to smartly manage interference in the radio spectrum via load-driven network selection and offloading schemes, distributed power control, opportunistic scheduling, and by properly supporting cooperative multipoint techniques (CoMP) in the backhaul. Similarly, fostering the formation of clusters of users and coordinating their access activity can yield coordinated resource utilisation, which would turn into higher throughputs.

### 2.2 Traffic-proportional energy consumption

It is a key challenge to obtain wireless network energy consumption proportional to the volume of handled traffic. The energy consumed by today's network wireless nodes is barely sensitive to the traffic flows over the wireless links. Therefore, in order to save energy, we aim at modulating the long-term activity cycle of each device, in both access and backhaul, based on traffic conditions, i.e., by using smart algorithms to switch on/off base stations and access points. Furthermore, the use of distributed management mobility (DMM) solutions, jointly with the location planning of mobility anchors throughout the backhaul, will enable routing optimisation aiming at reducing load and energy costs in the backhaul. On a short-term operation timescale, we target energy saving through energy-driven opportunistic transmissions, thus using the channel at its best conditions, thereby requiring less transmission power and reducing retransmissions due to channel errors. Ideally, energy costs can be made proportional to the traffic by reducing to zero the energy overhead to run the equipment. Therefore, we will compare the energy consumption of the nodes, in Joules per transmitted bit, to the energy consumed over the radio interface. Considering that wireless devices are commonly utilised at 20-30% of the nominal capacity, traffic-proportional mechanisms are then expected to reduce the power consumption by up to 70%. This figure can be further improved by optimising the routing for minimal energy consumption in the backhaul.

### 2.3 Mobile user's QoE

Another key challenge is to obtain a mobility management system that guarantees Quality of Experience to users moving through dense, small cells where connectivity management is particularly challenging for mobile users. We target session continuity with stable QoE of mobile users by means of inter-cell and inter-technology management mechanisms. To this aim, we will consider the exploitation of the 802.21-like handover paradigms, the use of reconfigurable backhauls, and the development of DMM solutions. This objective is measurable in terms of handover blocking probability and variation of average bandwidth and end-to-end delay experienced by mobile users. Additionally, we will measure the backhaul load reduction due to dynamic reconfiguration solutions and DMM, and count the number of realizable scenarios and customers that can be accommodated in the network with QoE guarantees, as compared to the case of static backhaul solutions.

## 3 State of the Art

In this section we review the state of the art on the main concepts relevant to very dense networking concepts. Specifically, we discuss relevant solutions and proposals for connectivity management, energy efficient operation, MAC optimisation for IEEE 802.11 and 3GPP LTE, and backhaul optimisation mechanisms. For each of such topics, we also enlighten control/re-configurability issues known from literature, and identify the main innovations brought by the CROWD project.

### 3.1 Connectivity Management

The mobility scenario depicted in this work is based on the latest Evolved Packet System (EPS) architecture specified by the 3GPP (release 11), being its key advantage its ability to integrate heterogeneous access networks within the same operator core. Despite of these improvements, mobile operators are facing problems dealing with the sharp traffic increase. One of the causes of these problems is the actual design of the mobility protocols themselves, which are centralised (GTP [1], PMIPv6 [2], and DSMIPv6 [3]) and require all traffic being routed through some entity in the operator core that anchors the IP addresses used by the mobile node. This central anchor point is in charge of tracking the location of the mobile and redirecting traffic towards its current location. This way of addressing mobility management has several limitations that have been identified in [4]:

- Sub-optimal routing. Since the traffic of the mobile node is anchored at the central entity, the packets must cross the operator network to reach the central anchor point before arriving at the terminal.

– Per-terminal mobility management. Current solutions are not able to discern traffic with mobility requirements from other traffic. Therefore, mobility management services are provided with no differentiation to all traffic flows.

Due to these limitations, which are common to most of the connectivity management protocols being currently deployed, the IETF is looking at new protocols with distributed nature. In particular, there is a working group about to be chartered, called Distributed Mobility Management (DMM), addressing distributed connectivity management issues for mobiles. In parallel, the issues above mentioned have triggered a similar response within the 3GPP that has started looking at connectivity management protocols in order to provide new traffic offload capabilities and perform local breakout (traffic is forwarded directly to Internet without going through the mobile operator network core) as close as possible to the user, hence reducing the load in the operator core. The most promising technologies developed by 3GPP are Selected IP Traffic Offload (SIPTO) and Local IP Access (LIPA) [5].

The key difference between these 3GPP approaches and IETF DMM is that 3GPP solutions are focused on providing localised mobility support, enabling the users to move while anchored to the same GW but they do not provide global mobility, requiring the PDN connections to be deactivated and re-activated when not moving locally. Conversely, thanks to its distributed nature, DMM provides global mobility management. Summarising, CROWD will specify novel DMM protocols providing mobility at flow level, that account for access and backhaul using heterogeneous wireless technologies.

### 3.2 Network energy saving mechanisms

Energy optimisation is nowadays drawing significant attention from the research community. Although much of the research in this area is focused on optimising the MAC and the physical layer of specific technologies (e.g., [6]), there is also significant work focused on reducing the overall energy footprint of complete networks. These ideas are built on top of the seminal work of Restrepo et al. [7], which introduced the idea of energy profile and the dependence of the energy consumption on the traffic load of a particular network component. Based on this work, in [8] some simple measurements about power consumption of networking devices are first presented; the authors then consider a network topology and evaluate the total network consumption given the power requirement of each element. Algorithms for selectively turning off base stations have been further proposed in the literature. Works as [9] and [10] investigated the possibility of switching off base stations in periods of under-utilisation. In [11] the authors propose to switch off nodes in areas with high density of routers. Results of such previous work show that the energy consumption can be reduced between 25-50%, at various times of the day, by using on-off techniques, although the association of users to the cell/AP must be controlled and new protocols must be designed to convey all the required information. Finally, Fehske et al. [12] investigate the possibility of lowering the energy consumption of cellular networks by deployment of small, low-power base stations, alongside the conventional sites. Their results show that the deployment of micro sites does not directly lead to a reduction in power consumption by relaxing the coverage requirements; however, it provides significant gains in spectral efficiency in high load scenarios.

The application of the existing algorithms mentioned above to very dense deployments of micro or femto cells alongside current macro cell deployments is not immediately obvious. In fact, on the one hand, dense deployments, along with agile algorithms to control the set of active base stations and wireless backhaul nodes, should improve efficiency. On the other hand, the denser and the more heterogeneous the deployment, the more difficult it becomes to compute optimisation solutions, and to supply input data for these optimisation algorithms.

### 3.3 MAC Enhancements for IEEE 802.11

The beahvior of IEEE 802.11 in dense deployments has been only partially addressed in the literature. Here we focus on the four technology aspects that are most relevant to CROWD: (*i*) MAC enhancements, (*ii*) multi-tier mechanisms, (*iii*) coordination techniques, and (*iv*) opportunistic medium access.

Regarding MAC enhancements, most of the work available in the literature addresses the problem of finding an optimal channel allocation. For instance, in [25] and [26] each AP chooses the best channel to operate based on the load of its neighbouring APs. The work in [27] and [31] focuses on heuristics for channel assignment in chaotic and dense wireless networks, referring with this term to the residential or urban areas where users deploy their networks without either taking too much care of AP configuration or considering the neighbouring APs configuration. Furthermore, authors of [28] propose a new 802.11-like MAC protocol (namely SRE MAC) in which the transmission priority of wireless stations adapts to the number of interfering stations, by tuning the contention window and the backoff parameters in either a centralised or distributed way.

A few multi-tier mechanisms using novel technologies such as Wi-Fi-Direct [29] have recently emerged, for instance [32] This mechanism takes advantage of the direct links temporarily established between wireless devices using Wi-Fi-Direct and inter-BSS Direct Link Setup (iDLS, [30]). The authors of [32] also report on prototypal implementation and experimental results. However, the application of such multi-tier mechanisms is not driven by network-wide optimisation objectives, and, in contrast to CROWD's vision, it does not account for inter-technology interoperation within the same transport session.

Within the category of coordination techniques, we found two kinds of works. First, there are analytical proposals focusing on the use of WLAN as a complementary tool for 3G networks [33]. Second, there are some studies and standardisation groups trying to coordinate different IEEE 802.11 APs to reduce interference and optimise channel allocation [34]. Again, existing work accounts for neither very high dense deployments nor for the presence of different wireless technologies, thereby requiring significant modifications to be adopted in the envisioned CROWD's framework.

Finally, opportunistic 802.11 networking is addressed in [35], which presents a mechanism that relies on open APs and spontaneous mobile devices working as APs. Furthermore, a few proposals on 802.11 modifications for distributed opportunistic scheduling have recently appeared. The authors of [36] and [37] take the first steps to study such mechanisms in which stations probe the channel and decide to transmit only if their channel quality is above a threshold, whereas the authors of [38] use control theory to analyse adaptive distributed opportunistic scheduling mechanisms. The available work focuses on MAC throughput optimisation. However, there is no solution available which aims at exploiting density as a resource.

### 3.4 3GPP LTE MAC optimisation

At radio access level, LTE exhibits increased peak rates and spectral efficiency, and reduced latency, with respect to its previous generations, i.e., UMTS, HSPA, and HSPA+ due to a combination of physical and MAC layer enhancements, including the use of OFDMA, MIMO, high-order modulations and efficient coding rates. However, a huge potential exists in LTE, which is not fully exploited yet in current deployments and has many research challenges associated: self-optimisation and Inter-Cell Interference Coordination (ICIC). Self-optimisation, constitutes, together with self-configuration and self-healing, the Self Organising Network (SON) vision of the 3GPP introduced in the Release 8 of LTE and supported at European level by the FP7-ICT project SOCRATES. A promising research direction of self-optimisation is optimised handover [13] [14]. Self-optimisation concepts are part of the main objectives of CROWD, which will study them from the perspective of a highly dense network, in the case of homogeneous technology, and will investigate opportunistic use of multiple technologies available for a given user. The problem of inter-cell interference has been long studied (e.g., [15] [16] [17]), but the main problem was the lack of standardised inter-cell signalling. LTE solved this problem, since the X2 interface has been defined for direct communication between eNBs. However, while the X2 opens the door to practical optimisations for dynamic interference management, new research challenges are also created since the abstract optimisation models developed are hardly applicable under the physical and protocol constraints of the X2. The issue is further complicated in the case of heterogeneous networks, e.g., overlapping macro-, pico-, and femto-cells in the same area, which is reference scenario for CROWD. While some efforts exist in this context, e.g., [18] [19] [20] [21], the research is still in its infancy, and all the studies so far only use analysis or simulations as a means for validation. In CROWD we will advance the state of the art by delving into the details of the technology and providing an assessment based on test-bed experiments to bridge the gap between mathematical modelling and optimisation and realistic application. Finally, another area that is especially relevant to the subject of highly dense networks is that of Machine-to-Machine (M2M) communications. It is expected that there will be an explosion of smart things that will become connected wirelessly to the future Internet in the next years. While 3GPP recognised that optimal network for Machine Type Communications may not be the same as the optimal network for human to human communications [22], the issue is not expected to be addressed before 3GPP Release 12. In CROWD the issue of scalability will be specifically addressed, and this will have indirect impact on the use of LTE for M2M applications, which will be reinforced by liaising with the technical committee in ETSI that is dedicated to M2M.

### 3.5 Backhaul Optimisation Mechanisms

So far backhaul requirements for cooperation techniques and the influence of a constrained backhauls have been researched extensively for current (i.e., sparse) network topologies and densities [23]. Furthermore, the implementation of dynamic backhaul reconfiguration has been studied for wired, optical or wireless point-to-point backhaul networks [24]. This research, shows that dynamic backhaul reconfiguration can enable complex coordination schemes, as well as improve the efficient usage of the backhaul network in terms of energy consumption and quality of user experience. Those current approaches are the first ones to exploit backhaul reconfiguration as a means to enhance cooperation techniques, but the usable degrees of freedom for backhaul reconfiguration are limited because of fixed topologies (often tree-like) and deployed technologies. With the high density of the analyzed scenario, a wireless backhaul with more flexible topology options is more likely and we expect to exploit the benefits of dynamic backhaul reconfiguration beyond the current approaches. With these approaches the backhaul capacity will be near-proportional to the traffic and capacity demands requested by the new coordination schemes

## 4 The CROWD approach

In the following we describe how the CROWD project approaches the key challenges specified in Section 2. These mechanisms and their interactions are illustrated in Fig. 2.

### 4.1 Connectivity management mechanisms

While dense networks offer new degrees of freedom that can be exploited by connectivity management schemes, they also pose some challenges to mobility. One of the key mechanisms of CROWD will be a connectivity management scheme that specifically targets session continuity (e.g., IP flow handover) in dense heterogeneous networks, network selection, and inter-technology coordination of LTE and 802.11. This will include: (i) investigating handover management at flow granularity, accounting for rapid variations of network conditions in dense environments; (ii) proposing network access schemes in presence of multiple candidate base stations, hotspot access points, and, possibly, ad-hoc relay nodes; (iii)

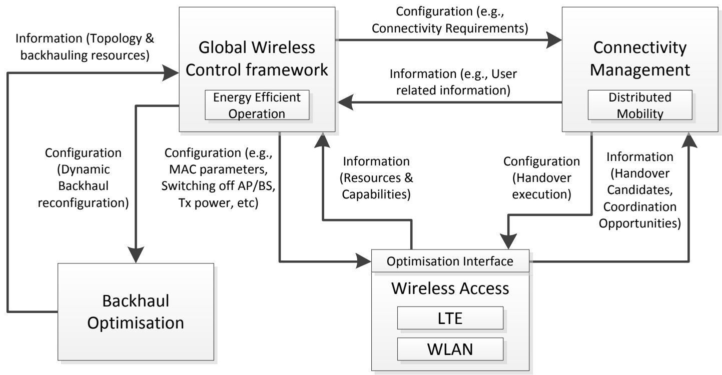


**Fig. 2.** Mechanisms tackled in CROWD and their relationship

developing clustering schemes for mobile users, in which groups of mobile users jointly request access to a base station through a few "opportunistically selected" nodes in the cluster, while the traffic is routed within the cluster by means of 802.11 (e.g., Wi-Fi direct); (iv) proposing distributed anchoring schemes for flows requiring mobility support, aiming at offloading the operator's network core from the huge traffic generated by user's demands. Overall, this connectivity management class of mechanisms aims at enhancing the Quality of Experience (QoE) of mobile users, and will therefore be evaluated in terms of outage probability, handover performance and bandwidth that can be guaranteed to mobile users in challenging mobility scenarios.

### 4.2 Energy efficient operation mechanisms

In traditional WLAN and cellular systems, energy does not scale with transmission distance or with volume of exchanged data. In fact, the power consumption of access points and base stations is rather constant or only slightly affected by the effective traffic load of the device ( 10% variation). In this scenario, the CROWD project will tackle network-wide energy efficiency by targeting traffic-proportional wireless operations, e.g., by designing solutions for dynamically reconfiguring the topology of the wireless network. This will be done by exploiting an integrated operation/management of multiple heterogeneous access technologies, such as activating and deactivating cells and hotspots in a coordinated way while maintaining enough coverage to meet user's demands. The energy efficient operation mechanisms will be tightly synchronised with the connectivity management mechanisms described above, to ensure connectivity to all users.

### 4.3 MAC optimisation mechanisms for 802.11

The IEEE 802.11 MAC parameters such as the backoff counter and inter-frame spacing, as well as MAC mechanisms such as rate adaptation, were not designed for dense and interference-prone deployments. Hence, we will analyse MAC misbehaviours and non-optimal MAC operations in presence of multiple interfering cells. We will also study the importance and limits of 802.11 MAC parameters and mechanisms when very small cells come into play, including power control, coordinated sleep cycles and distributed opportunistic medium-access techniques. Due to their inherent ability to optimise resource utilisation and minimise interference, these techniques aim at enhancing 802.11 MAC flexibility, thus yielding better configurability in interference-prone and dense scenarios. Considering the drawbacks of using unmanaged 802.11 wireless deployments with multiple access points operating on same or adjacent channels, typically driving to deep spatial performance bias, or even starvation, we expect that (distributed) coordination will bring dramatic improvements in terms of capacity, fairness, and predictability of performance. The techniques designed will rely on a number of parameters that will be configured by a global control framework to optimise the overall performance.

### 4.4 MAC optimisation mechanisms for LTE

In LTE, the most important optimisations are executed in the MAC, at Radio Resource Control (RRC) level, hosted by the base station. Among other mechanisms, scheduling, link adaptation and power control have a critical impact on optimisation, which is exacerbated further in highly dense networks. Noticeably, even though an interface for direct communication between base stations for handover related information, is defined by the standard, namely X2, that interface is not used for optimisations (i.e., in practice most of today's optimisations happen with local/cell-based scope). In contrast, CROWD will consider scheduling, link adaptation and power control for a leapfrogging technology advance based on inter-cell coordination, e.g., via X2. As for the metrics to evaluate the efficiency of the proposed mechanisms, we will not only use the aggregate network throughput, but also the available spatial and frequency reuse factors, which measure the ability of our schemes to reduce unnecessary interference by coordinating adjacent cells. Furthermore, ideal cell coordination would allow for performance to scale with the cell density, hence we aim at approximating such a scaling behaviour, and thus we will use distance between the proposed mechanisms and the ideal case as a metric of our success.

### 4.5 Backhaul optimisation mechanisms

As the wireless backhaul may potentially become the bottleneck for performance, we need to dynamically configure it for optimal performance. To this end, we will extend existing techniques for backhaul configuration to a wider range of backhaul technologies (wireless or wired) and make these backhauls reconfigurable to adapt them to the concrete traffic needs. Specifically, the project targets backhaul flexibility in terms of (i) traffic-proportional reconfiguration strategies, e.g., temporary pruning underutilised and unneeded backhaul nodes, (ii) on-demand capacity-injection strategies, e.g., reconfiguring the backhaul topology to sustain currently high-loaded areas and using cooperative multipoint techniques. With respect to current static backhauls, we expect to achieve traffic-proportional energy costs, and a considerably higher number of realizable scenarios (i.e., scenarios where all the demands can be satisfied).

### 4.6 Global control framework

In order to ensure that we bring the network to global optimal performance, all the previous mechanisms need to be configured by a global control framework. For instance, if connectivity management and backhaul optimisation are configured separately, performance will be suboptimal as compared to the case when they are jointly optimised. The same holds for the energy-efficient operation and the MAC optimisation mechanisms. In order to address this, CROWD will rely on a global control framework that interfaces with all the mechanisms and configures them for global optimal operation.As many of the control functions have stringent data rate or delay requirements towards multiple base stations or access points, one of the key issues that will be investigated in CROWD is the optimal location of such global decision points. For instance, some of the MAC layer techniques described above—like coordinated inactivity cycles and scheduling across cells—need to locate control decisions somewhere in the network where such processing functions can be executed with stringent delay requirements.

## 5 Conclusions

We foresee in the near future an explosion of new services that will require an increase in the bandwidth available to the end-user. There are several potential mechanisms to provide such an increased bandwidth, such as making available more spectrum, optimizing or developing new technologies and decreasing the size of the cell range. Historically, the approach more successful in terms of the increase of bandwidth consequence of its use, has been the decrease on the cell range. This is the approach followed by the CROWD project, providing higher capacity to the end-user by densifying the access network. This paper has presented the key challenges and concepts behind the CROWD initiative.

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