ICT-777137

5G-RANGE

5G-RANGE: Remote Area Access Network for the 5th Generation

Research and Innovation Action

H2020-EUB-2017 – EU-BRAZIL Joint Call

D6.1: Software-based system integration

Due date of deliverable: 30th June 2019

Actual submission date:

Start date of project: 1 November 2017 Duration: 30 months

Lead contractor for this deliverable: UFC and UC3M

Version 1 date 30th June 2019

Confidentiality status: Public

Abstract

This deliverable shows the integration of the multiple block in the 5G-RANGE PHY, cognitive MAC and Network layers. A software simulator was used to perform and test this integration. The PHY layer has been simulated using Matlab and C languages, providing link level block error rate for the cognitive MAC and network simulator, which has been implemented in NS3. The integrate software simulator will be used to analyze the system performance and also to show 5G-RANGE features that will not be present in the proof-of-concept testbed. The PoC will be used to demonstrate three use cases defined in D2.1 and the SDR approach employed in its development will lead to an advanced TRL prototype, which will be easily transferable to the market.

Target audience

The primary target audience for this document is the radio access network research and development community, particularly those with an interest in mobile communication physical and MAC layers. This material can be fully understood by readers with a background in mobile wireless cellular systems, especially those familiar with 3GPP standards for 4G and 5G.

Impressum

Full project title: 5G-RANGE: Remote Area Access Network for the 5th Generation

Document title: D6.1 - Software-based system integration

Editor: Luciano Leonel Mendes, Inatel (BR)

Project Co-ordinator: Marcelo Bagnulo, UC3M (EU), Priscila Solis, UnB (BR)

Technical Manager: Luciano Mendes, Inatel (BR), Yaning Zou, TUD (EU)

WP leaders: Ivo Bizon , TUD (EU), Luciano Mendes, Inatel (BR)

This project is co-funded by the European Union through the ICT programme under H2020.

Executive Summary

The 5G-RANGE network has been designed to support a large set of services in remote area, covering several use cases, as described in D2.1. However, the evaluation of all 5G-RANGE features demands the implementation of the entire architecture described in D2.2. Budget and time restrictions hidden the implementation of all features in the real-time proof-of concept. Therefore, a software simulator has been developed to demonstrate all capabilities of the 5G-RANGE Network, while the proof-of-concept will cover the most important use cases, which are voice and data connectivity, smart farms and wireless backhaul.

The system simulator is composed by a link-level simulator and a system level simulator. The link-level simulator is able to analyse the physical layer performance in terms of bit error rate and block error rate under different channel conditions. All numerologies and features have been implemented in the link-level simulator. This simulator has provided block error rate curves that feeds the system level simulator, abstracting the physical layer. With these curves, the behaviour of the PHY layer can be mapped in a set of tables that are accessed to inform the performance of the lower layer. With this approach, the performance of the entire network can be simulated in a feasible amount of time.

The strategy for the proof-of-concept consists on use most of the functions developed for the system simulator, including for physical layer. Hence, a new platform based on general purpose processors and software defined radio will be employed for the next phase of the prototypes. However, the physical layer has blocks that are very complex and time-consuming to be executed on a processor. In this case, a hardware accelerator will be used to improve the overall system throughput. The hybrid platform will allow the re-use of most functions developed for the system simulation, reducing the risk and time for the proof-of-conception implementation. This new strategy will also increase the time readiness level of the prototypes, allow for a smooth transfer of the project outcome to the telecommunication market.

List of Authors

Carlos Filipe Moreira e Silva (UFC)

Diego Aguiar Sousa (UFC)

Ivo Bizon Franco de Almeida (TUD)

Luciano Leonel Mendes (Inatel)

Tarcisio Ferreira Maciel (UFC)

Yuri Carvalho Barbosa Silva (UFC)

Luis Pacheco (UnB)

Geraldo Pereira Filho (UnB)

Priscila Solis (UnB)

Cristoffer Leite (UnB)

Marcos Caetano (UnB)

Wheberth Damascena Dias (Inatel)

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Definitions and Abbreviations

A + P	Address plus Port
Adj-Rib-In	Adjacent Routing Information Base, Incoming
AJAX	Asynchronous JavaScript and XML
AMC	Adaptive Modulation and Coding
AMF	Access and Mobility Management function
API	Application Programming Interface
ARP	Address Resolution Protocol
AS	Autonomous System
ASIC	Application Specific Integrated Circuit
AUSF	Authentication Server Function
AWGN	Additive White Gaussian Noise
BER	Bit Error Rate
BGP	Border Gateway Protocol
BLER	Block Error Rate
BRAS	Broadband Remote Access Server
BS	Base Station
CB	Code Block
CDF	Cumulative Distribution Function
CDL	Cluster-Delay Line
CGN	Carrier Grade NAT
CFO	Carrier Frequency Offset
CMAC	Cognitive Medium Access Control
COTS	Common of-the-shelf
CP	Cyclic Prefix
CQI	Channel Quality Indicator
C-RAN	Cloud Radio Access Network
CS	Cyclic Suffix
CSI	Channel State Information
D2D	Device-to-Device Communication
DCI	Download Control Information
DDoS	Distributed Denial of Service
DNS	Domain Name System
DoS	Denial of Service
DPD	Digital Pre-distortion
DSL	Digital Subscriber Line
DSLAM	DSL Access Multiplexer
DSA	Dynamic Spectrum Allocation
eBGP	External BGP
ECR	Effective Code Rate
EESM	Exponential Effective SINR Mapping
ESM	Effective SINR Mapping
FCFS	First-Come First-Serve
FEC	Forward Error Control
FFT	Fast Fourier Transform
FPGA	Field Programmable Gate Array
GbE	Gigabit Ethernet
GFDM	Generalized Frequency Division Multiplexing
GPP	General-Purpose Processors
HARQ	Hybrid Automatic Request
HDL	Hardware Description Language
HGW	Home Gateway

IANA	Internet Assigned Numbers Authority
iBGP	Internal BGP
IETF	Internet Engineering Task Force
IFPI	Interference Free Pilot Insertion
IMD	Intermodulation Distortion
ISP	Internet Service Provider
L2S	Link-to-System
LISP	Locator/ID Separation Protocol
LLC	Logical Link Control
LoS	Line of Sight
LSN	Large Scale NAT
LSM	Link to System Mapping
MCS	Modulation and Coding Scheme
MED	Multi-Exit Discriminator
MIMO	Multiple-Input Multiple-Output
MIESM	Mutual Information Effective SINR Mapping
MSE	Mean Square Error
MSL	Maximum Segment Lifetime
MTC	Machine Type Communications
NAT	Network Address Translation
NIC	Network Interface Card
NFV	Network Function Virtualization
NFVI	Network Function Virtualized Infrastructure
NFVO	NFV Orchestrator
NLoS	Non-Line of Sight
NRF	Network Repository Function
NSSF	Network Slice Selection Function
OFDM	Orthogonal Frequency Division Multiplexing
OOBE	Out-of-Band Emissions
OS	Operational System
P2P	Point-to-point
PC	Programmable Computer
PHY	Physical Layer
PI	Provider Independent
PoC	Proof-of-Concept
PSS	Pilot Synchronization Signal
QAM	Quadrature Amplitude Modulation
QPSK	Quadrature Phase-Shift Keying
RA	Resource Allocation
RB	Resource Block
RBG	Resource Block Group
RIR	Regional Internet Registry
r.m.s	Root Mean Square
RFPA	Radiofrequency Power Amplifier
SAVI	Source Address Validation Improvements
SDR	Software-Defined Radio
SDU	Service Data Unit
SE	Spectrum Efficiency
SINR	Signal-to-Interference-plus-Noise Ratio
SLS	System-Level Simulator
SNR	Signal-to-Noise Ratio
SMF	Session Management function

SRS	Sound Reference Signal
SoC	System-on-Chip
SS	Spectrum Sensing
SUAV	Small Unmanned Aerial Vehicle
TB	Transport Block
TCB	Transmission Control Block
TRL	Technology Readiness Level
TVWS	TV White Space
UCI	Unique Client Identifier
UE	User Equipment
USRP	Universal Software Radio Peripheral
VIM	Virtual Infrastructure Management
VNF	Virtual Network Functions
VNFM	VNF Manager

1 Introduction

The 5G-RANGE network has been designed to provide reliable broadband access connection, IoT services and support for vehicle communication in remote areas. 5G-RANGE will introduce a new operational mode for 5G, expanding its applicability for a true universal internet access, with significant positive social and economic impacts in uncovered and underserved areas.

The aim of this document is to present the overall system integration using a software platform in order to demonstrate all possibilities of this innovative 5G network. The Physical Layer (PHY) blocks designed and specified in WP3 are combined with the Cognitive Medium Access Control (CMAC) developed in WP4 and with the network functions from WP5. The result is a simulation platform that can be used to evaluate the overall system performance and also to demonstrate features that will not be available in the proof-of-concept (PoC) demonstrator.

The main strategy in this system integration consists on using an event-based environment, called NS-3, to integrate all the CMAC and Network functions in order to create a system level simulator. The PHY will be abstracted through a set of block error rate (BLER) performance curves, which are provided by a PHY simulator developed using Matlab and C/C++. The overall system simulator is a reference design for the final PoC that will be deployed in Santa Rita to Sapucaí.

The development of the PHY and MAC functions for the software simulator has shown that current general-purpose processors (GPP) can perform the digital signal processing at high data rates. This means that most of the functions can be executed by the GPP, in a software-defined radio (SDR) approach. This strategy reduces the development time, simplifies the PoC implementation and also increases the system flexibility. Nevertheless, some blocks on the receiver side, i.e. the channel decoders, demand a high level of parallelization and its implementation in a field programmable gate array (FPGA) is more efficient. Hence, a hybrid architecture, based on software and hardware implementation, will be employed for the PoC.

Besides presenting the system integration, this document also describes all the features of the final PoC and describes the scenario of the final 5G-RANGE demonstration. A table describing the expected technology readiness level (TRL) for each component of the 5G-RANGE system will be presented.

1.1 Deliverable Structure

The remaining of this document is structured as following: Section 2 describes the 5G-RANGE system, with details of the PHY block integration and MAC block integration. The control channel, necessary for allowing new devices to be connected to the network and also for supporting the spectrum sensing reporting from the user equipment (UE) to the base station (BS), is described in detail. Section 3 shows the details about the system simulator. The link-level simulator for the PHY and the CMAC simulators are presented, including all interface and integration among these layers. The numerical results and the BLER performance curves from the PHY simulator are discussed as well. Section 4 details the features that will be implemented in the PoC, as well the description of the final demonstration that will be deployed in Santa Rita do Sapucaí. Section 5 brings the TRL table of the main components of the 5G-RANGE network together with our vision for the future products. Finally, Section 6 concludes this document.

2 5G-RANGE System

The 5G-RANGE architecture is composed by three layers, namely, PHY, CMAC and Network layers. Each layer is composed by a set of functions and blocks that can be combined to provide different features. The following subsections describe the main blocks that compose each layer, including the integration among them.

2.1 PHY Layer

The 5G-RANGE PHY layer has received several new features to address the requirements for a remote area operation. The integration among the blocks that compose this layer and the implementation tools used to build the simulator are crucial also for the PoC. The idea is to reuse most of the functions developed for the software simulator also for the real-time demonstrator, improving the implementation efficiency of the project and reducing the risks involved with the PoC.

2.1.1 Platform solutions for the PHY implementation

The actual implementation of communication systems requires that the signal processing algorithms of the transmitter and receiver chain run in real-time. Deployed systems can achieve this goal using Application-Specific Integrated Circuits (ASICs), Field-Programmable Gate Arrays (FPGAs), Software Defined Radio (SDR), or System-on-Chip (SoC) baseband processors (Liu, 2015).

An ASIC can offer high performance, in terms of the number of signal processing operations per time unit. The power consumption per operation is also small on these devices, which can extend the battery life in mobile, or Internet of Things (IoT) devices. Once an ASIC is developed, your function is fixed and changes cannot be made to the deployed devices. This, in turn, limit its use to applications where high performance is strictly necessary or no changes are expected in the system operation, such as mature or legacy communication systems. ASICs also require less silicon area to perform a given task, when compared with other implementation solutions, which translates in a lower cost per device.

Unlike an ASIC, the FPGA can be reprogrammable on the field, while still offering a good performance in terms of processing power. This makes the FPGA attractive for deployments of systems in constant evolution such as LTE, 5G-NR and many others. The development of systems implemented in FPGAs is usually less expensive than ASICs since no tooling costs are required. FPGAs are extensively used to build prototype systems before developing the ASIC-based solution. The power consumption of FPGAs is higher than the consumption of an ASIC to perform the same task. The unit cost of an FPGA is also high when compared to an ASIC because FPGAs consumes a relatively large silicon area for its reconfiguration ability. The ability to update the implementation after deployment and the good processing power makes the FPGA a good solution for base station implementation, while its unitary cost and higher power consumption are less attractive for mobile devices.

The baseband SoC are programmable devices usually with many processing cores inside one chip. Its architecture is formed by CPU cores and specialized hardware to perform specific and high demanding tasks, common in communication systems, such as Fast Fourier Transform (FFT). The baseband SoCs can achieve both, high performance and flexibility, while achieves low power consumption (Liu, 2015). The baseband SoCs currently are the main technology used in mobile devices.

The SDR enables the development of reconfigurable wireless systems that run in a programmable platform. This allows all the physical layer functions to be implemented in software on a single device, which usually can be accomplished via a common programmable computer (PC).

The hardware-based approaches provide high performance and efficiency while, on the other hand, lack the flexibility of function reconfiguration and present relatively long development cycles. Moreover, SDR is a less expensive solution when compared with dedicated hardware solutions.

A GSM-like cost effective cellular solution for remote areas has been tested in Tanzania employing open-source SDR. The authors demonstrated a low-cost prototype cellular network operating via SDR, and show that voice calls and SMS exchange can be accomplished by already market available GSM mobile devices [7]. Similarly, authors in [8] present a simple and cost-effective GSM network implementation using SDRs, specifically employing the Universal Software Radio Peripheral (USRP). Therefore, SDR seems the most reasonable choice for creating novel and cost-effective cellular networks in remote and rural areas. Given these points, the 5G-RANGE PoC shall be implemented using SDR.

The PHY of the 5G RANGE transceiver for the PoC will be, mostly, implemented using SDR in the GNU Radio (GNU Radio Foundation, 2019) platform. GNU Radio is a free and open-source toolkit to implement software radios. It is not only suitable for wireless communications research, but also for real-world deployment of communication systems. The GNU Radio platform allows the implementation of wireless communication algorithms in C/C++ and Python languages targeting common off-the-shelf (COTS) GPP architectures, such as x86, x86_64 and ARM.

The use of COTS hardware makes possible to employ the SDR code developed with GNU Radio in a large variety of hardware, ranging from many multi-core processors, as required in Cloud Radio Access Networks (C-RAN), to low-power embedded processors.

The SDR approach enables the development of low-cost base station and user equipment, based in commodity hardware computers, bringing the 5G-RANGE system closer to deployment in real-world applications. The use of high-level languages offers a big advantage in the development cycle, when compared with hardware description languages as VHDL and Verilog targeting FPGAs. Although, FPGAs achieve higher processing throughput due to the degree of parallelism natively achieved in these devices.

Tasks such as Polar decoding and the baseband pre-distortion are very demanding and may jeopardize the 5G-RANGE 100 Mbps goal (5G-RANGE, April 2018) if implemented entirely in software. The addition of an FPGA card, acting as an accelerator, can address the processing bottlenecks of the transceiver hardware architecture. The GNU Radio platform allows calls to the Application Programming Interface (API), needed to offload processing tasks to the FPGA board.

2.1.2 Transceiver chain overview

This section describes the implementation of the signal processing chains employed at the downlink and uplink for the 5G-RANGE PoC. The description of both, transmitter and receiver chains, will be described next.

2.1.2.1 Downlink signal processing chain

In the downlink, the PHY is responsible for receiving the Transport Blocks (TB) from the MAC layer, process and transmit it according to MAC layer request. The parameters that need to be defined for the transmission of each TB are system numerology, MIMO scheme, modulation order, code rate, allocation on the resource grid and power offset.

The PHY layer processes each TB individually and maps to the requested location on the resource grid. Once all information for a given subframe is processed, the transmission takes place. Figure 1 depicts how the information is mapped from from the MAC layer to the resource grid.

To allow coexistence in TVWS, the MAC layer will only allocate data to be transmitted where the spectrum is free, as indicated by database or spectrum sensing algorithms.

In addition to this, the MAC informs the PHY which resource blocks are allowed for transmission on every subframe. With this information, the 5G RANGE PHY can confine the reference signals only in the bandwidth occupied by the secondary band. The TB are independently processed at the PHY level up to the waveform modulation, where all blocks of a given subframe must be processed at once. Therefore, it is possible to employs several processing units working in parallel in order to increase the overall system throughput. .

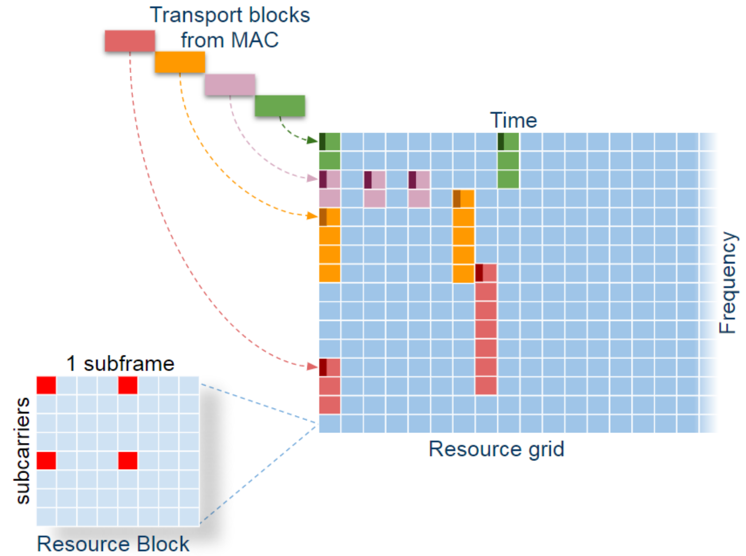

Figure 1. Transport block allocation to the resource grid.

The transmitter chain for the downlink includes channel coding, QAM modulation, MIMO coding, layer mapping, waveform modulation, frame multiplexing and digital pre-distortion. Figure 2 shows the block diagram of the downlink transmitter of the base station. Section 2.1.2.2 describes the role of each block.

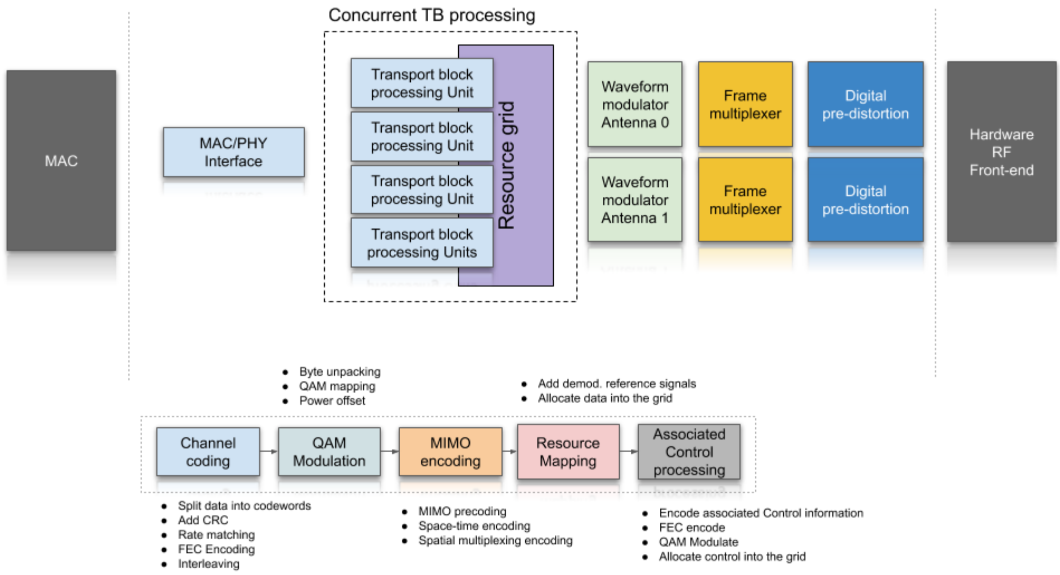

Figure 2. Block diagram of the BS transmitter at the downlink.

At the downlink, the PoC base station (BS) transmits the Downlink Control Information (DCI) to allow the user equipment (UE) to correctly find and receive the TB designated for it. On the PoC, the PHY includes the DCI for every transport packet processed. The DCI information is located at the resource elements on the beginning of the allocation. The UE searches for this information to successfully locate and receive the resources allocated to it in the grid.

The downlink receiver, at the UE, is responsible for receiving the TB allocated to it, and deliver the TB to the UE MAC. Along with the data, the PHY also sends the channel state information (CSI) metrics related to the reception of a particular TB. This information is reported to the BS MAC, allowing the link adaptation process to be executed.

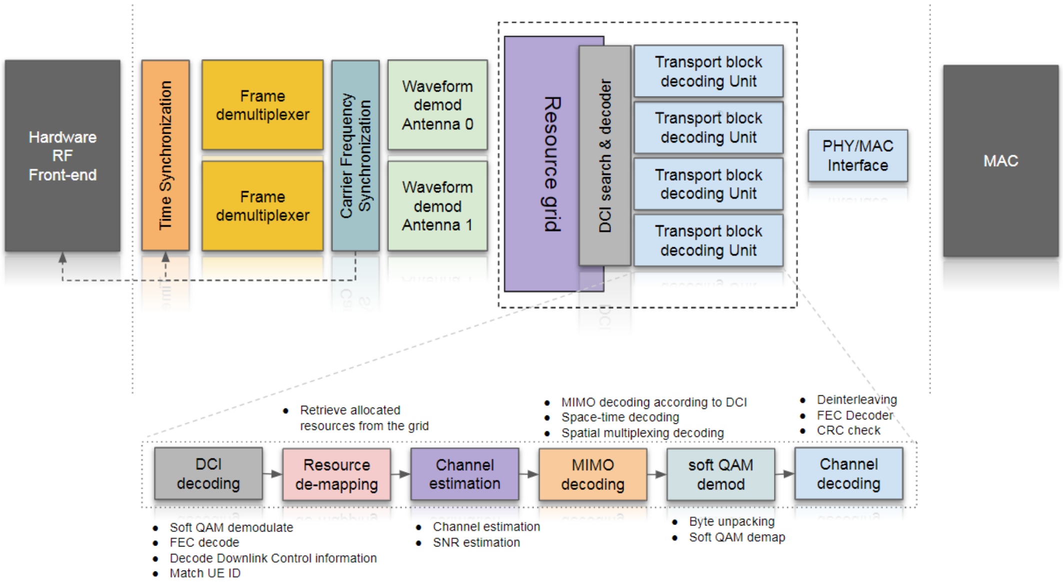

Figure 3. Block diagram of the UE Receiver at the downlink.

The downlink receiver at the UE uses the primary synchronization signal (PSS) located on the start of the frame to acquire the required symbol timing for the next processing operations. The carrier frequency offset (CFO) also needs to be estimated and corrected. The frame timings and estimation of the CFO are also used to make all uplink transmissions synchronous to the downlink.

2.1.2.2 Signal processing blocks

Channel encoder

On the 5G-RANGE system, when the MAC layer has information to be sent to the user equipment, the MAC layer must select the code rate according to the channel state. the MAC then allocate the resources for the transmission. The longer block size possible is chosen for a given amount of resources allocated.

The channel encoding function is responsible to implement the 5G-ACRA algorithms. It takes as input the transport block data and encodes with the coding rate and block size requested by the MAC layer. This block takes as input the number of information bits to be sent and the size of the allocation and encodes the data. The code rate is derived from the ratio between the number of information bits and the number of bits available on the specified allocation.

The rate matching uses the Polar code length immediately longer than the number of bits available in the allocation and punctures the codeword to fit in the available slot. If the number of the coded bits in a transport block is longer than the maximum codeword specified for the 5G-ACRA, the transport block is segmented by the channel encoder. The bit interleaving operation is also performed by the encoder block. On the PoC, the block size will be limited to 2048 bits.

QAM Modulation

This function is responsible to map the encoded bits to the QAM constellation selected by the MAC layer. In addition to that, the QAM symbols are scaled to allow the MAC layer to change the transmission power for a particular user and implement a power control loop.

The code rate is chosen according to the CSI. The block size is determined based on the amount of data available to be transmitted to the user.

MIMO Encoding

This function is responsible to implement the MIMO algorithms defined by the 5G-MIMORA. The QAM modulated symbols are mapped to the transmitter antennas according to the channel status and MIMO capabilities of the UE as indicated by the MAC. This block performs the space-time encoding or spatial multiplexing and generates the encoded symbols to be transmitted at each antenna. The PoC will be able to handle up to 2x2 MIMO for diversity or spatial multiplexing.

Resource Mapper

The resource mapper assembles the MIMO encoded symbols of the transport packet to its corresponding resource elements within the resource grid. This function also positions the demodulation reference signals used for proper equalization at the receiver.

DCI encoding

This function encodes the DCI associated to the allocation of the transport packet and maps it to the grid. The DCI message contains the information required by the UE to correctly receive and demodulate the transport packet. The DCI message is encoded with a fixed code rate and mapped to QPSK symbols. It occupies a reserved space, at the beginning of the allocation in which the transport packet will be carried. A cyclical redundant check code (CRC) of the DCI is scrambled using the ID, equivalent to the Radio Network Temporary Identifier, allowing different UEs to be individually targeted

Waveform Modulator

The waveform modulator generates the OFDM or GFDM waveforms according to the 5G-FlexNOW specification. This block is responsible for providing the numerology requested by MAC layer. It takes as input a matrix of complex numbers representing the resource grid and generates the waveform symbols to be transmitted. The waveform modulator also inserts the cyclic prefix (CP) and cyclic suffix (CS) to the waveform block and perform the time windowing for reducing the OOBE.

Frame Multiplexer:

The frame multiplexer is responsible for inserting the sync reference signals and the silence period at each frame. The silent period will allow the cognitive cycle to perform the spectrum sensing within the occupied bandwidth. Hence, primary users that start operation in the bands used by the 5G-RANGE network can be detected and the cognitive cycle can initialize the procedures for changing the operation frequency.

Digital pre-distortion (DPD):

The Radio Frequency Power Amplifiers (RFPA) employed in digital transmitters are non-linear devices. The nonlinearity results in spectral regrowth at its output, affecting the in-band signal quality and OOBE (Rodrigues, Pimenta, Souza , & Mendes, 2018). The baseband DPD aims for reducing the amount of intermodulation distortions (IMD) by introducing an inverse distortion on the signal before amplification. This is accomplished by modelling the behaviour of the RFPA (Silveira, 2007) and creating an inverse model to cancel the distortion at its output.

The baseband DPD process is non-linear and creates IMD products. Although this effect is wanted, it requires an oversampling, regarding the Nyquist sampling frequency, of the undistorted signal, otherwise, the IMD products, required for the linearization process, may suffer aliasing reducing the efficacy of the pre-distortion algorithm.

In theory, to cancel third order IMD products, the DPD bandwidth and RF front-end must be capable to generate a bandwidth three times higher than the desired signal. If the 5^{th} order IMD must be canceled, then the oversampling is five times higher than the Nyquist frequency (Yu, Qianyun, Honglei, Xingwang, & Xiao-We, 2018). Considering the 5G-RANGE system with a 24 MHz bandwidth, it means that the pre-distortion system must operate at sample rate of approximately 72 MHz. This is very demanding for an SDR implementation and the acceleration of this task using a FPGA is likely to be employed.

Time synchronization:

The time synchronization block at the receiver is responsible to correctly determine the frame timing. The algorithm used to achieve synchronization is based on the cross-correlation with a known sequence, named Primary Synchronization Signal (PSS). In SDR, the cross-correlation can be efficiently implemented using Fast Fourier Transform (FFT) and the overlap-and-save convolution algorithm. The first sample of the frame is marked, so the next blocks can correctly receive the signal. The timing extracted at the downlink is also employed to synchronize the UE transmissions in the uplink direction.

Carrier frequency synchronization:

The carrier frequency offset (CFO) of the UE local oscillator is estimated observing the downlink carrier frequency. For the PoC implementation, this value will be derived from the phase the cross-correlation between CP and the corresponding part of the symbol. The CFO correction is accomplished in a closed loop fashion, in such way that the correction is applied prior to any processing. This allows all blocks, including the time synchronization, to take advantage of the CFO correction.

The signals transmitted by the UE in the uplink direction must be corrected to account for the CFO perceived in the downlink. This ensures that the transmission of all UEs are frequency synchronized at the base station receiver.

DCI Search and decoding procedure

The waveform demodulation decodes the received signal, recovering the resource grid. Each UE performs a sequential search for the DCI in the symbols at the beginning of all resource blocks. In this procedure, the UE tries to decode the DCI, and check the CRC of the decoded information. As the CRC is scrambled using the UE ID, this check will be successful only if the received information is a valid DCI and the ID of the UE is the same ID used to encode the information. The UE is then able extract all the information required for recovering the transport block from the resource grid. The DCI decoding involves equalization of the control information, QPSK demodulation, Polar decoding and CRC checking. The transport block decoding is accomplished by reversing the order of the operations executed at the transmitter. The PHY send the decoded transport block to the MAC layer, along with the channel state metrics associated to its reception for link adaptation purposes.

FPGA acceleration

Despite the power of the current general-purpose processors, the Polar decoding process and the digital pre-distorter are very demanding tasks. The software implementation of these tasks may not be able to achieve the real-time performance to implement the 5G-RANGE PHY to run entirely in a GPP. One alternative is to use an FPGA connected to the PCIe bus to offload the processing of those demanding tasks. This strategy is being considered for the PoC implementation, since the polar decoder and the DPD are already implemented in Hardware Description Language (HDL), this code can be reused in this application.

2.1.2.3 Uplink signal processing chain

In the uplink direction, the signal processing chain is basically the same for the downlink. The main difference is that all transmissions in the uplink direction must be synchronized with the downlink. The downlink is used as time and frequency reference for all UEs connected to the gNB and the transmissions in the uplink direction are frequency shifted to account for the error of the local oscillator of the UE.

In the uplink direction, every UE is allowed to transmit just in the resource blocks assigned to it. The MAC of the UE only requests transmissions to the PHY on those resources. Taking this in account, most of the PHY processing blocks in the uplink direction are the same as in the downlink, being the main exceptions the frequency synchronization block, not needed at the uplink, and the frame multiplexer, which must receive timing information from the downlink to synchronize the uplink transmissions.

2.2 MAC Layer Integration

The MAC layer implementation for PoC is focused on a subset of the 5G-RANGE MAC layer specified in the documents D4.1, D4.2, and D4.3, including the cognition functions and a basic implementation of the MAC layer that will run in a dedicated high processing platform. The integration with the upper layer IP applications will be done by a physical Network Interface Card (NIC), basically a Gigabit Ethernet (GbE) interface. The integration with the PHY will be done via an Application Programming Interface (API), considering a single platform for the MAC and part of the PHY layers.

Figure 4 shows a basic view of the MAC layer components and interconnections, including the MAC controller and the MAC manager that control all L2 system and handle the configuration parameters, logs and traces.

This MAC implementation is the same for the gNB and for the UE, and is divided in higher MAC and lower MAC, where the first one handles the user plane application IP packets through the NIC, and the last one handles the user plane TB, and also the control plane through the MAC and PHY interface.

The Linux system provides the networking functions with complete network protocol stack integrated with the NIC, with the kernel providing structured implementation of these functions. The MAC implementation is based on a GNU/Linux based Operating System (OS) with the source code modified to accommodate the MAC layer functionalities specifics for the PoC. The higher MAC is a basic Linux system handling networking functions related to the IEEE 802.11 Logical Link Control (LLC) layer. The lower MAC is complemented by additional functions specified for the 5G-RANGE MAC layer that will be developed in C or C++ language. The upper layer solution is a L2 solution, meaning that 5G-RANGE network provides a L2 forwarding functions of frames carrying encapsulated IP packets originated or to be delivered to external networks or devices.

Figure 5 provides options for PoC deployment where the 5G-RANGE network is essentially a layer 2 network that allows the transport of IP packets and Address Resolution Protocol (ARP) frames with ARP tables with dynamic entries. Another option is to manually configure theARP tables, including static L2 forwarding tables. In Figure 5-a) there´s only PC stations connected to the 5G-RANGE network and, in this case, the PC connected to the gNB is the application server, and two different PCs with application clients connected to the UEs. In Figure 5-b) the gNB is connected to the public Internet network allowing access to the applications located in the cloud.

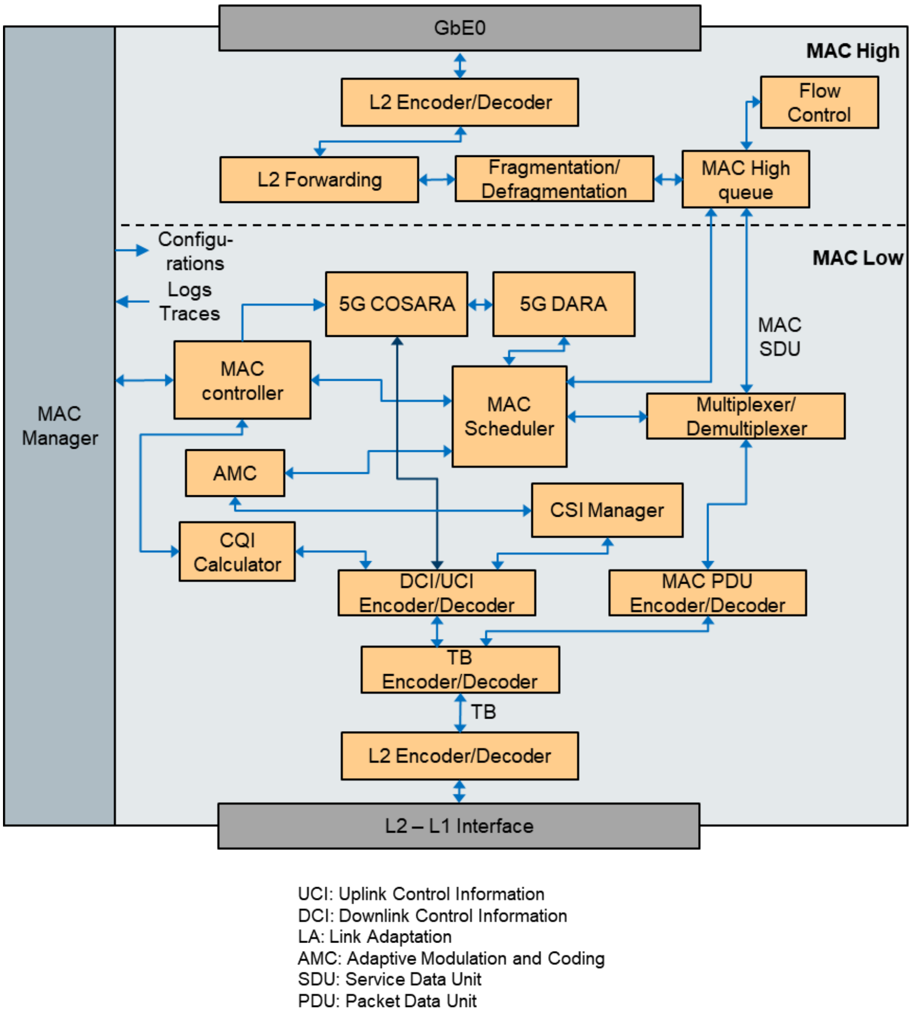

Figure 4. Basic view of the MAC layer components.

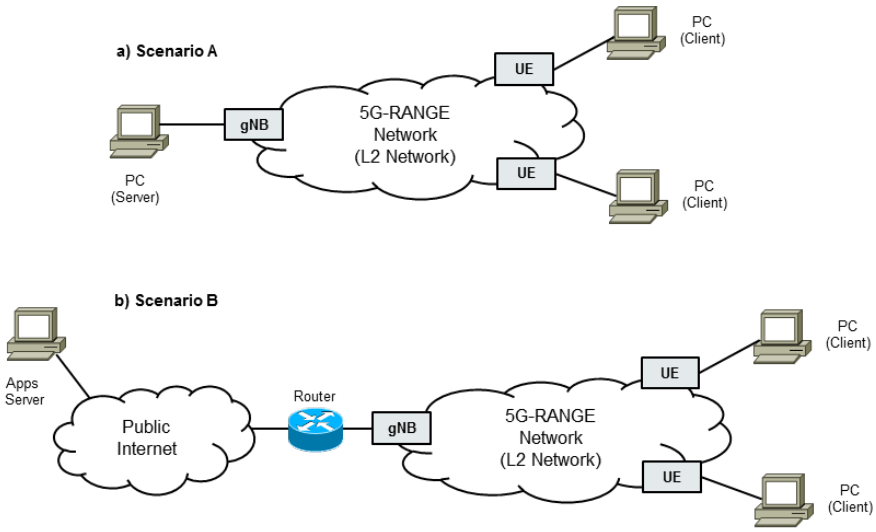

Figure 5. Options for PoC deployment for the 5G-RANGE network interconnections.

2.3 Network Layer Integration

The Network Layer implementation aims to deploy a complete virtualised environment with network functions. To deliver this, it follows the non-roaming 5G System Architecture defined by ETSI TS 123 501 V15.5.0. Figure 6 depicts how the components interact and their interfaces on a service-based design. The goal is to deliver end-to-end network slicing, a 5G foundation responsible for supporting a plethora of new generation use cases and for allowing a logical evolution of the mobile technology. The project also aims to extend the network coverage beyond the limits of the radio cells and to provide a cost-effective solution with an alternative low-cost scenario. Small Unmanned Aerial Vehicles (SUAVs) and ground units (e.g., harvesters, tractors, sprayers, etc.) with onboard computer, storage & network resources will integrate a low-cost and power-constrained Network Function Virtualised Infrastructure (NFVI).

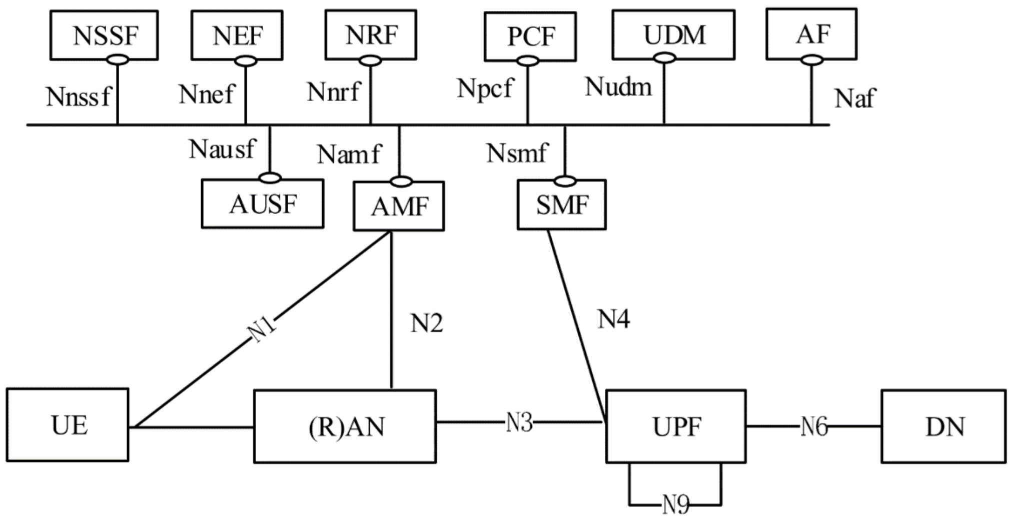

Figure 6. Non-roaming 5G Core Network architecture using service-based model.

The integration with upper and lower layers will be done using these 5G Core network functions, such as Access and Mobility Management function (AMF) and Session Management function (SMF), on a virtualised environment. To do this, the project will implement a complete Network Function Virtualisation (NFV) following ETSI NFV architecture and using Virtualised Network Functions (VNFs) of 5G Core components. The deployed scenario of virtualized services allows the functional split that 5G stack expects and provide the overall architecture with programmable computing capabilities and softwarized resources. Figure 7 shows how virtualised functions give the integration of such an environment following 5G Core requirements and ESI NFV. The NFV ETSI definition can be implemented using NFVs orchestrators and managers, supported by open source software. This type of approach enables a flexible and cost-effective implementation of network services and the strategy that will be adopted to simulate the network layer based on the ETSI NFV specification will be further described in Section 3.

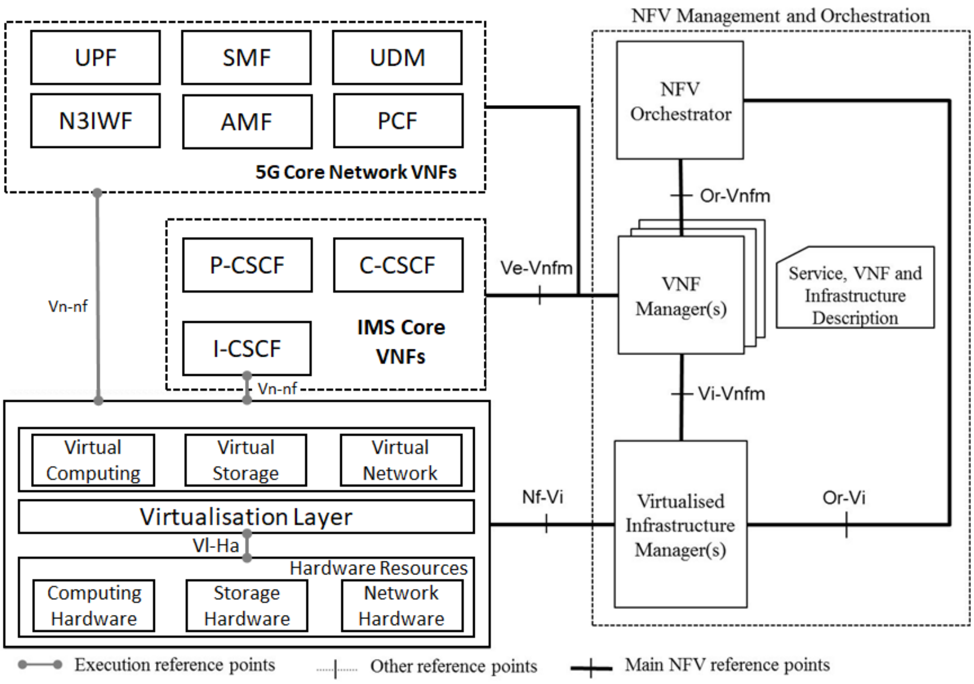

Figure 7. ETSI Network Function Virtualisation Architecture

2.3.1 Interfaces and APIs

5G-RANGE network layer is a group of modularized Network Functions providing and consuming micro-services over the unified medium defined by 5G Core Network Architecture. To deliver their services to other functions, they register available APIs on a central catalogue called Network Repository Function (NRF). The NRF also contains information of all accessible service and data service outputs, acting as a centralised service broker. Another essential function is the Network Slice Selection Function (NSSF), responsible for network slicing selection and instantiation. NSSF defines how the infrastructure must be divided on a virtualised level.

2.4 Control Channel Integration

The 5G-RANGE system implements flexible resource allocation, numerology selection and MIMO scheme selection, to cope with the uncertainty of spectrum availability and adapt to the actual channel state. In order to allow the dynamic selection of parameters, control information must be exchanged between the UE and the network. The control messages can be originated at the core of the network, at the MAC layer, or at the PHY layer. This section will focus on the control messages originated at the MAC and PHY layers. The messages originated at layers above the MAC are treated by higher layers and are not described in this section.

2.4.1 Control messages between the gNB MAC and gNB PHY

The PHY is responsible for the transmission of all information over the air. In order to do so, the PHY offers the transmission of transport packets as a service to the MAC layer. The control information between PHY and MAC of the same node (gNB or UE) is an API call and a communication between these two instances and this information is not transmitted over the air.

Send Transport Block message

Request the transmission of a transport block over the air with numerology. With this message, the gNB or UE MAC requests the transmission of a transport block to the PHY. The MAC must specify the numerology, MIMO scheme, target UE ID, Modulation, code rate and the resource blocks to be used in the transmission. The data to be transmitted is also supplied along with the configuration.

Start of subframe message

With this message, the MAC informs the PHY that all transport block requests of the current sub-frame have ended and the subsequent requests shall be transmitted on the next subframe. The MAC must inform the numerology and the resource blocks available to transmission on the new sub-frame. The PHY uses this information to configure the waveform modulator and to contain all reference signals within the allowed spectrum.

Transport packet received

This message is sent by the UE or gNB PHY to the MAC when a transport packet is received. It contains the data received along with the ID of the sender, employed resources, numerology, modulation, code rate, and the channel metrics related to the reception of this transport block, including the current channel quality indicator (CQI).

2.4.2 Control messages between the gNB PHY and UE PHY

Downlink / Uplink control message

These messages are generated at the PHY layer transmitter of the gNB or UE to allow the counterpart receiver to correctly demodulate and decode the transport block. These messages contain information about the allocation in the resource grid, MIMO scheme, modulation and code rate and UE ID employed at the transmitter. In the downlink direction, due to the UE ID the receiver is able to identify if the transport block is targeted at it or at another UE. In the uplink direction, it allows the gNB to identify the UE responsible for the transmission.

The downlink and uplink control messages are transmitted over-the-air and occupy the first resource elements of the resource blocks allocated to a given transmission. The of resource elements for the DCI is known by the MAC and accounted for during the resource allocation procedure.

Erro! Fonte de referência não encontrada. shows the main control messages endpoints and the message type between the endpoints.

Table 1. Control message endpoints and message types.

Source / destination		Interface	Information
gNB MAC	gNB PHY	API Call	Spectrum resources available
gNB PHY	UE PHY	Over-the-air (DCCH)	downlink / uplink control information
gNB MAC	UE MAC	Over-the-air (DSCH)	Uplink resource reservation

3 System Simulator

The 5G-RANGE system simulator will be used to analyse the full potential of the proposed network. The simulator will be composed by a link-level analysis tool, a link-to-system interface and a cognitive MAC simulator. These tools are described in detail below.

3.1 Link-level Simulator

The 5G-RANGE operation scenarios imply different PHY requirements when compared with 5G NR. For instance, dynamic and non-continuous spectrum allocation, robustness against severe multipath and high Doppler shifts, high spectrum efficiency, run-time configurable equipment, and waveform with low OOBE without RF filter are characteristics that shall be present on the 5G-RANGE PHY.

As demonstrated in D3.1 and D3.2, Generalized Frequency Division Frequency Multiplexing (GFDM) presents the best overall performance when compared to other multicarrier waveforms. Notably, GFDM waveform exhibits low levels of OOB emission and offers good CP efficiency, which are required characteristics for operation on TVWS and channels with long delay profiles. Thus, GFDM has been chosen as the multicarrier modulation scheme for 5G-FlexNOW.

The performance analysis and specification of forward error correction (FEC) codes and proposal of 5G-ACRA (5G Advanced Coding for Remote Areas) have been carried out in D3.2. The remarkable performance of Polar codes under the 5G-RANGE channel model led us to choose this scheme for 5G-ACRA and, as pointed out in D3.2, this channel coding scheme is well suited to work in the very challenging 5G-RANGE scenario, meaning that it presents acceptable performance while keeping feasible decoding complexity.

The tasks of synchronization and channel estimation are defined in the scope of 5G-IR2A (Inner Receiver for Remote Area Applications). The 5G-RANGE PHY is a fully synchronous system, and the synchronization scheme is based on finding the peak from the cross-correlation between reference and received signals. Differently from 5G NR, the 5G-RANGE IR2A has to get information about the operating frequency before carrying out the synchronization and channel estimation procedures. This is due to the fact that 5G-RANGE has to be able to operate in fragmented spectrum. The channel estimation technique uses interference-free pilot insertion (IFPI) as described in D3.2. Briefly, the actual channel estimation is executed via an advanced algorithm that considers the information on the pilots as well as the information contained in the CP.

The MIMO scheme employed by the 5G-RANGE PHY, referred as 5G-MIMORA, will be based on space-time coding aiming for diversity gain and special multiplexing, i.e., improving BER performance for a given SNR or improving the data rate. Furthermore, 5G-MIMORA will employ dual polarized antennas for coping with the antenna array size in the UHF band. As the results from initial investigation shown in D3.2, the dual polarization architecture is critical for achieving the 100 Mbps KPI.

Regarding the channel model, special care has been taken as to account for the spatial and time correlation of the channel present in a wireless cellular system. In deliverable D3.1 [1], a stochastic geometric channel model has been proposed for 5G-RANGE. Regarding large-scale fading, the proposed model was built upon the results published by Ericsson & Telstra of a measurement campaign in different remote area scenarios [9],[10],[11]. A regression analysis was applied on the available data and path-loss and shadowing have been extracted for characterizing the 5G-RANGE remote/rural area scenarios.

In wireless communication, fading is variation of the attenuation of a signal with several variables. These variables include: time, geographical position, and radio frequency. Moreover, short-term fading is often modeled as a multi-variable random process. In the same deliverable, a proposal for the short-term fading has also been made based on the data of Ericsson & Telstra measurement campaign [9],[10],[11]. As a result, short-term fading was modeled according to a cluster-delay line (CDL) channel model considering the 3GPP power-delay profiles CDL_A (NLoS) and CDL_D (LoS), in which multiple rays with different angles of departure and arrival are combined to produce channel components over a number of spatial clusters so that frequency, time, and angular (spatial) correlation are considered.

In particular, the delay and angular spreads of the original CDL profiles were suitably rescaled to meet the typical remote/rural delay and angular parameters. For more details about the 5G-RANGE channel model, please refer to deliverable D3.1 [1].

3.2 Link-to-system Interface

The link-level simulator described in the previous section is adequate for obtaining results relative to the transmitter and receiver structures, such as channel coding algorithms, waveform parameters, channel estimation, equalization, detection, among others. Nevertheless, when considering the overall system with several links, and considering scheduling and interference aspects, it no longer becomes possible to assess system performance by simulating the bit transmissions of each individual link [2].

As it is commonly considered in literature, the PHY can be abstracted by means of a link-to-system (L2S) interface [3]. Such interface maps the link-level performance metrics to the system-level, thus allowing the system-level simulator (SLS) to model the link characteristics as accurately as possible and with low computational complexity. The link performance can be measured in terms of metrics such as the bit error rate (BER) and block error rate (BLER), whereas the signal-to-noise ratio (SNR) and the signal-to-interference-plus-noise ratio (SINR) are typical system level metrics. Throughout this section, the SINR and SNR terms can be used interchangeably, when assuming that the interference is negligible or unlikely, such as in the case of the very large cell scenarios of 5G-RANGE.

In multi-channel systems, in particular, the effective SINR mapping (ESM) model is able to capture the effect of having different link qualities when data is multiplexed over multiple communication resources, such as the RBs in 5G-RANGE.

The mapping of the ESM model is done in two steps. First, the individual SINR of all resources are measured at the system-level and mapped to an effective SINR ($SINR_{eff}$), which represents the average quality of the link. Then, this effective SINR is mapped to a BLER value, which can be used at the system-level to determine whether the transmission of a specific set of data has been successful or not, thus allowing the computation of system throughput measures. These steps can be represented by the following functions:

$$SINR_{eff} = r(SINR),$$

$$BLER = \xi\left(SINR_{eff}\right),$$

where the compression function r maps the measured set of individual SINR values to a single effective SINR, and the ξ function maps the effective SINR to BLER. These mapping functions consider the specific transmission parameters, such as modulation and coding schemes. Figure 8 presents an illustration of the L2S interface considering these mapping functions.

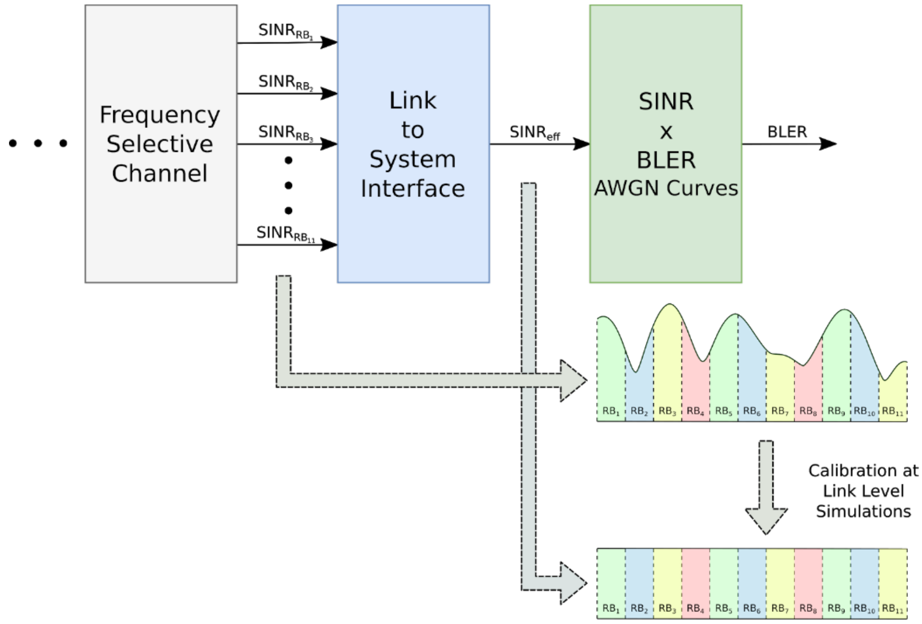

Figure 8. Link-to-system (L2S) interface modeling.

Note that in the case in which a single SINR value is involved in the transmission, i.e., when a single resource or a single measurement of a set of resources is used, the compression function $r(SINR)$ reduces itself to the identity and $SINR_{eff} = SINR$. Also, in this case, if the mapping from SINR to BLER is available, it could be used directly instead of implementing a fitting function to map it onto an additive white Gaussian noise (AWGN) link performance curve.

Several mapping techniques have been previously investigated in the literature, but the exponential effective SINR mapping (EESM) and mutual information effective SINR mapping (MIESM) techniques have shown a high accuracy performance [3]. However, since the EESM is the simplest one and does not diverge much from the MIESM, it was the selected technique for the L2S interface to be used in the 5G-RANGE project.

The EESM provides a way to translate a block of varying channel SINR values to an effective SINR value, of which the BLER in an AWGN channel is equivalent to. The EESM algorithm has been proposed originally for single-antenna systems, but through improvements it can be applied as an L2S interface for MIMO systems as well. The EESM model, as its name refers, computes the information measure based on the exponential function. The final derivation of the formula is as follows:

$$SINR_{eff} = -\beta \ln\left(\frac{1}{N}\sum_{k=1}^{N} \exp\left(-\frac{SINR_k}{\beta}\right)\right),$$

where N represents the number of used resources and $SINR_k$ stands for the SINR measure at a specific resource k.

Again, whenever the transmission involves a single resource, the fitting parameter β and the non-linear averaging mapping involved to compute the $SINR_{eff}$ can be simplified and, according to the case, the associated SINR versus BLER performance mapping (from the fading channel) can be used directly without fitting it back to the AWGN SINR versus BLER performance.

The EESM technique considers the β parameter as a calibration factor whose value is chosen to minimize the root mean square (r.m.s) error between the effective SNR, derived from the fading channel, and the static average SNR which leads to the same BLER value in a AWGN channel. The β parameter is an approximation value that compensates the modulation alphabet, the coding rate and the block length of the transmitted block [4]. To calculate the β parameter, the following expression is used:

$$r.m.s = \frac{1}{S}\sum_{s=1}^{S}\left(SNR_{eff_s} - SNR_{static_s}\right)^2, \text{ and}$$

$$\beta = \text{argmin}(r.m.s).$$

Note that the objective function of the β optimization can also consider the difference between the actual and the mapped BLER, which should achieve similar results. Furthermore, it is possible to consider not all of the resources involved in a multi-resource transmission but only a subset, as long as the frequency spacing between two SINR values does not exceed half of the coherence bandwidth [4].

The final part of the L2S interface is predicting the BLER. Thus, the L2S interface predicts the BLER based on the $SINR_{eff}$ value, which corresponds to multi-state values associated with the block being transmitted, and an AWGN or a channel-specific link level performance. These data are simulated in advance and made available as look-up tables for each modulation and coding scheme (MCS). The BLER mapping is important because it must guarantee a target SINR threshold for switching from/to an MCS, which in cellular systems is commonly set to the SINR value that yields 10% of BLER. Once an $SINR_{eff}$ value is obtained and mapped to a BLER value P_{BLER}, a uniformly distributed random value p between 0 and 1 can be generated and used to determine the failure (in case $0 \leq p \leq P_{BLER}$) or the success (in case $P_{BLER} < p \leq 1$) of the block transmission.

The 5G-RANGE link-level simulator has been used to generate the BLER results required by the L2S mapping interface for the different link configurations and numerologies, which included a total of 27 MCSs, 6 numerologies, 6 different average mobile speeds, and 3 channel models/profiles. Given the large amount of simulations that need to be run in order to obtain all results, computational performance becomes a critical issue. For this reason, some parts of the link level simulator have been optimized, such as the LDPC and polar encoder/decoder, as well as the 5G-RANGE channel model. More details on the generated results and adopted parameters are presented later in this document.

3.3 Cognitive MAC Simulator

The 5G-RANGE System-level Simulator is based on the Network Simulator 3 (NS-3), and the 5G-RANGE Cognitive MAC layer will be integrated in the NS-3 code. It does not implement link-level simulation, meaning that the PHY is abstracted, and for that it implements the L2S interface with post processed PHY BLER curves. NS-3 code is implemented in the C++ language and is structured in modules, and the main ones are the: Core module; Network module; and Transport module, and a complete description is provided in D4.4.

NS-3 includes the MAC scheduler that works with MCS module to determine the TB bit capacity for user data transmission and provides the TB to the PHY, to the Channel Model for TB transmission and reception simulation.

It implements the Resource Allocation Type 0 grouping the use data bits in Resource Block Groups (RBG) of different sizes determining frequency domain resource allocation. The MAC TB implementation provided by the simulator is simplified with respect to the 3GPP specification, with the class `PacketBurst` used to aggregate MAC Service Data Unit (SDU).

D4.3 described the Cognitive Cycle specified for the 5G-RANGE system, with the 5G-RANGE MAC and PHY layers integrated with the 3GPP standard procedures. Changes is required to include the Fusion Algorithm with the 5G-COSORA module, and the Spectrum Allocation function with the 5G-DARA module. Considering the use of standard Channel State Information (CSI) procedure for Spectrum Sensing (SS) report management, the change in NS-3 is the use of the DCI for SS report request and unique client identifier (UCI) for SS report transmission, with addition of a new format for both control channels. The 5G-SCHED includes the MAC scheduler adapted for Cognitive Cycle Spectrum Allocation function and Resource Allocation (RA). Considering the use of aggregated TVWS channels of maximum bandwidth size of 24 MHz, with a resolution of 6 MHz for each TV channel, this implementation is already done and described in D4.4. Changes included the `LteSpectrumPhy` class to check the DCI for unused RBs, `LteSpectrumPhy::StartRX` to allow the forwarding to a sensing function (Sense), the `LteSpectrumPhy::StartRxDlCtrl` function was also modified to allow the reception of control messages with sensing results.

The primary user detection is based on post processed probability of detection tables provided by execution of a collaborative sensing algorithm in MATLAB. D4.4 presents the overview of the simulation architecture or setup implemented with Cognitive Cycle simulation performed using MATLAB tables, and NS-3 system simulation using the propagation models defined for 5G-RANGE scenario.

3.3.1 NS-3 Adaptations for the PHY and MAC Layers

The first part of the implementation of the 5G-RANGE Cognitive Cycle into the NS-3/LTE required the adaptation and inclusion of specific functionalities into the multiple classes available of the NS-3/LTE implementation, as was described in D4.4. The 5G-RANGE project proposes a licensed control channel and a TVWS 24 MHz bandwidth divided into 3 x 8 MHz (Europe) or 4 x 6 MHz (Brazil) data channels. The implementation of the separated control channel in the NS-3/LENA was not trivial, and was described in the preliminary results in D4.4. The 5G-RANGE PHY will be integrated into the simulator in Work Package 6, specifically in this task (6.1) and then will be validated in Task 6.3 using as reference the use case scenarios described in D2.2. The results in D6.3 may provide feedback on how to improve and optimize the Cognitive MAC layer.

This section describes the adaptations that were made in the NS-3/LTE implementation to include the 5G-RANGE PHY regarding frame structure, bandwidth and RBGs. Also, this section shows a preliminary performance evaluation of the 5G-Range PHY in the NS-3/LENA simulator, that brings the validation of the implemented code and its functionalities.

For further details, the updated code developed in this task is available at: https://github.com/Gabrielcarvfer/NS3/tree/5gphy.

Frame Structure Adaptations

The defined frame structure of 5G-RANGE is different from the one implemented in the NS-3/LENA. Therefore, the time subframe was changed to 4.6ms for all the proposed numerologies that will be used in the different use case scenarios, unlike for the LTE, which was maintained in 1msfor compatibility purposes. To implement the new subframe, a new macro called SUBFRAME_DURATION was developed in the lte-common.h file. Such a macro was used in various parts of the NS-3/LENA. Also, to set the duration time of the data channel and control channel transmission in a subframe, two constants of the `LteEnbPhy` class were changed:

DL_DATA_DURATION and;

DL_CTRL_DELAY_FROM_SUBFRAME_START.

To establish control between the UE and the gNB, the `LteEnbRrc` class that defines the standard RRC layer for the gNodeB were updated by the SUBFRAME_DURATION macro. Note that the SUBFRAME_DURATION macro was used to parameterize the duration of a subframe for the `LtePhy` class.

Bandwidth Adaptations for TVWS

The bandwidth change affects the number of resource blocks and the calculation of RBGs. This information is needed in various parts of the simulation code and its calculation is performed several times at different stages. The bandwidth range of 5G-RANGE are from 170 to 400 MHz and from 450 to 700 MHz. To enable the implementation of these bandwidths in the simulator, it was necessary to update the table E-UTRA Channel Numbers, in the lte-spectrum-value-helper.cc file. With this, it was possible to use the new frequencies to be set in each stage of the simulation.

The bandwidth is related to the number of resource blocks. The waveform and modulation described in the 5G-RANGE PHY allows no guard band among the RBs. Therefore, the number of RBs increases. To implement this feature, the mapping between the number of RBs and the bandwidth were made into the following classes: (i) `LteSpectrumValueHelper`; (ii) `ComponentCarrier`; and (iii)

`LteEnbNetDevice`. These classes were updated with the bandwidths of 8MHz and 6MHz (as was planned in D4.4) which have 44 RBs and 33 RBs, respectively.

The 5G-RANGE allows the use of 3 bands of 8MHz or 4 bands of 6 MHz, for a total of 24 MHz in both cases. In the simulation environment of the NS-3/LENA, both situations are made possible using Carrier Aggregation. However, a single band of 24 MHz was also created, since the scheduling algorithm may have control over all the available bandwidth.

Resource Block Group Adaptations

The specification of LTE sets up a minimum amount of Resource Blocks to be allocated to a single UE. The mapping is defined by Table 2, and varies from 1 to 4 RBs. 5G-RANGE recommends the allocation of 1 RB, to increase the granularity of the scheduler control. The values defined in Table 2 were present in several classes of the NS-3/LTE original implementation. To implement the functionalities of the 5G-RANGE, the `RbgAllocation` class in the lte-common.cc file that has the static `GetRbgSize` method was developed. This method returns the size of RBG 1 if the band used is defined by the 5G-RANGE.

Table 2: LTE system bandwidth and RBG size mapping

Bandwidth (MHz)	RBG Size
1.4	1
3	2
5	2
10	3
15	4
20	4

Code Validation and Evaluation

During the code adaptations and modifications, partial validations were made using simple simulation scenarios and execution logs. To validate the changes regarding the subframe duration, number of Resource Blocks and the Transport Block Size, several simulations were performed with different UEs (1, 10, 20, 30, 50, 100 and 132). In all the simulations, the channel conditions were considered optimal, so no packet retransmissions were performed. Moreover, the maximum code block size was used, which is 5888 bits per Resource Block.

In the validation scenarios the number of UEs nodes vary from 1 to 132, all sending packets with 736 bytes (in this case, the maximum quantity that fits a single Resource Block) at the subframe interval (i.e., 4.6 milliseconds) to a single point. Figure 9 shows the results concerning the 5G-RANGE Link-to-System (L2S) validation, illustrating a comparative analysis between the expected and achieved throughputs. As described before, the purpose of an L2S is to abstract the PHY at a fraction of the complexity of the detailed link-level simulations.

The results in Figure 9 compare the Maximum, Expected and Achieved throughput in Mbps. The Maximum (straight-line in clear blue) shows the maximum achievable theoretical throughput of 5G-RANGE, which was taken from Table 12 of D3.2. As can be seen, the Expected and Achieved Results are compatible and also limited by the theoretical throughput. This shows that the simulated results reflect the expected throughputs and are a first demonstration that validates the implementation of the 5G-RANGE PHY in the NS-3/LENA.

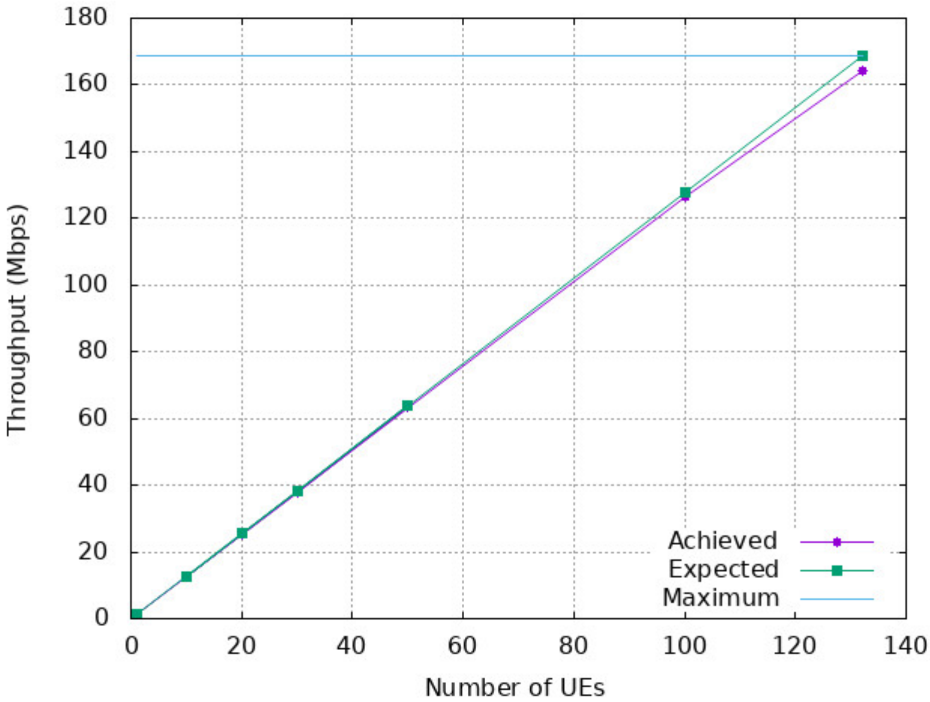

Figure 9: 5G-RANGE L2S

3.4 Network Simulator

The 5G-RANGE Network Layer PoC follows the overall architecture presented on D2.2 and the initial definition described on Deliverable 5.1 presented the end-to-end IP connectivity to the UE. 5G-RANGE seeks to meet the requirements of 5G-PPP Architectural Work Group, so both definitions follow the specifications given by ETSI TS 123 501 V15.5.0 for a 5G Core Network Architecture using the reference point model. The implementation uses ETSI NFV as its foundation and deploys all its main components defined by existing standards bodies, but also considers and complements the solutions adopted at the lower levels: i.e., physical and cognitive MAC layers.

Following NFV ETSI definition, the five main components to enable a fully NFV architecture are:

- An assortment of Virtual Network Functions (VNFs) that perform 5G Core Network functions, such as AMF, SMF, Authentication Server Function (AUSF), etc.
- The NFV Infrastructure (NFVI), which corresponds to all available computing, storage and network resources;
- VNF Manager (VNFM) coordinates all VNF lifecycle management;
- The Virtual Infrastructure Management (VIM), which controls all interactions between the upper software stratum and the bottom hardware resources of computing, storage and network.
- The NFV Orchestrator (NFVO), responsible for allocating available software resources to demanding VNFs and also for service realisation on the NFVI

3.4.1 Architecture Implementation

To improve overall cost and general performance by dynamically allocating available resources, the presented model fully employs a 5G NFV architecture and its components. Figure 10 depicts the implementation of the network-level architecture using ETSI NFV. Open Source MANO acts as NFV Orchestrator and VNF Manager, while OpenStack controls the VIM. These choices follow the de-facto standard software used by other 5G-PPP projects. Each 5G Core Function has a corresponding VNF available for deployment and respects the functional description given by ETSI TS 123 501 V15.5.0 for NF discovery and selection.

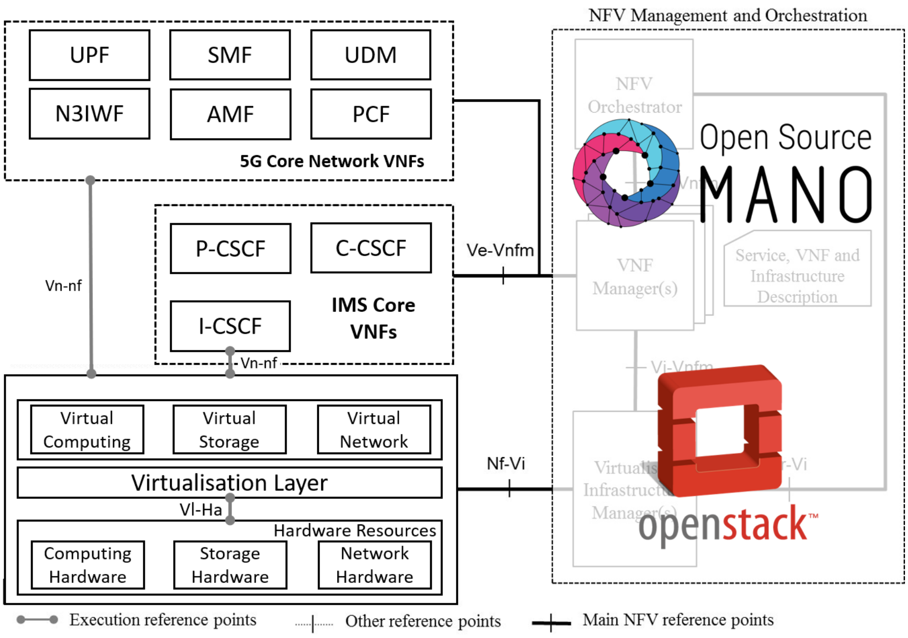

Figure 10. Overview of the network-level deployment for 5G-RANGE

This configuration enables a flexible, automated, and cost-effective implementation of network services over such infrastructure, while also following ETSI guidelines for virtualized network environments.

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3.5 System Simulator Integration Implementations

This section provides the implementation description of the LS2 and SLS functionalities considering integration of changes required in NS-3 code.

3.5.1 NS-3 Link-to-System (L2S) Interface Implementations

As described in section 3.2, the L2S interface function is to provide parameters considering the physical layer abstraction in the system simulation, mapping the link-level performance metrics to the system-level, measured in terms of metrics such as BLER and SINR.

In order to simplify the obtaining of the $SINR_{eff}$ in the 5G-RANGE Module, it was decided to use the EESM technique based on the Chernoff Union bound as L2S Interface, since this technique gets good results with low complexity in comparison to MIESM. As the EESM does not use the MI values, it is easy to get the look-up tables and the Link-to-System Mapping (LSM), because only the β parameter is necessary. As mentioned in the previous sections, since in most of the cases a Code Block (CB) does not spread over multiple RBs and since one can consider the approach of individually decoding CBs within a TB, the 5G-RANGE module can make use of the direct mapping of SINR (or $SINR_{eff}$) values to BLER values and embed the link-level performance curves into the SLS. Again, it is worth mentioning the all the combinations of CB sizes, MCS, numerologies and mobile speeds have been simulated using the LLS and are currently available for integration into the SLS.

The error rate curves for each MCS (i.e., 0 to 27) have been evaluated with a simulation campaign with the Link-level Simulator for a single link with the 5G-RANGE channel model and for 9 CB sizes. Furthermore, curves to SISO, MIMO 2x2 and MIMO 4x4 antenna schemes need to be provided, considering the concept of numerology used in the 5G-RANGE System.

In our proposed channel error model, the TB is divided in N_{K-} code blocks of size K- and N_{K+} code blocks of size K+. Therefore, the overall TB BLER can be expressed as

$$TBLER = 1 - \prod_{i=1}^{C}(1 - CBLER_i),$$

where the $CBLER_i$ is the BLER of the CB i obtained according to the link-level simulations curves within one of 9 CB sizes. For estimating the $CBLER_i$, the look-up tables to each code block are used jointly with the $SINR_{eff}$ got from the EESM technique. As mentioned in the previous section, according to the interleaving assumption over CBs belonging to a TB, they might be decoded and successfully received individually or as a whole in the TB.

Figure 11 depicts the process to determine the BLER of the TB received by the gNB or UE. Using AWGN or channel-specific BLER curves, $SINR_{eff}$ is mapped to BLER. The BLER values vary from 0 to 1, in which 0 means that the block does not have any error probability and 1 means that the block has 100% of error probability. Then, it is decided via a uniform random test whether the given received TB (or each of its composing CBs) was (were) received correctly.

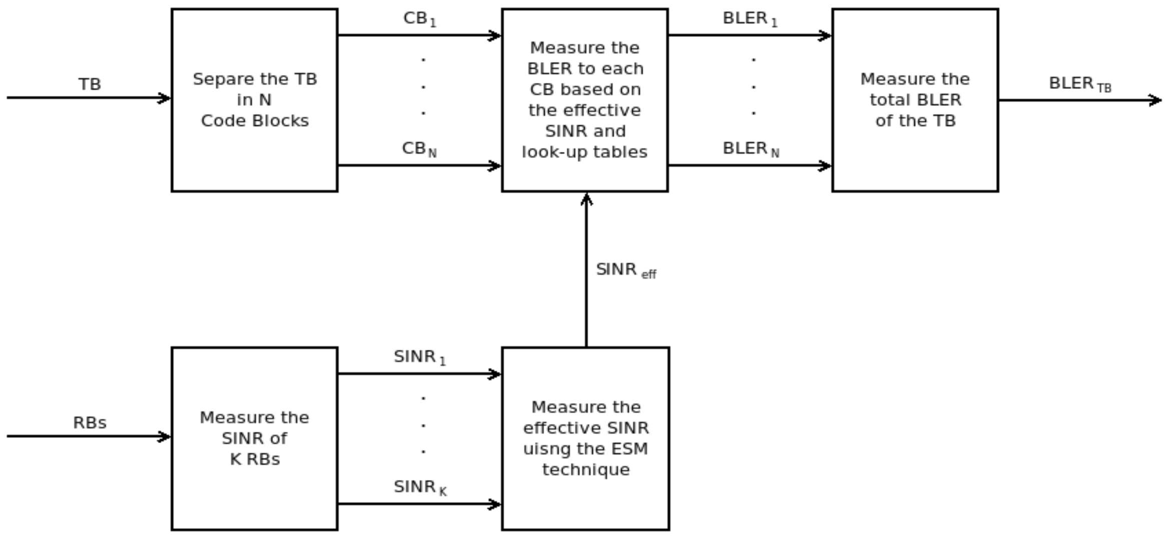

Figure 11. NS-3 implementation of the L2S interface providing the $SINR_{eff}$ and BLER.

NS-3 channel model abstracts the link layer, by performing the L2S interface as within the channel model an error model. The simulator includes an error model of the data plane (i.e., PDSCH and PUSCH) according to the standard LSM techniques.

Figure 12 shows the Downlink PDSCH transmission where the error model is triggered when a StartTx event is initiated involving SpectrumPhy and Spectrum Channel models. The reception occurs when the StartRx event is scheduled and initiated, triggering the error model process.

The SINR in the downlink is calculated for each RB assigned to data transmissions by dividing the power of the intended signal from the considered BS by the sum of the noise power plus all the transmissions on the same RB coming from other BS (the interference signals).

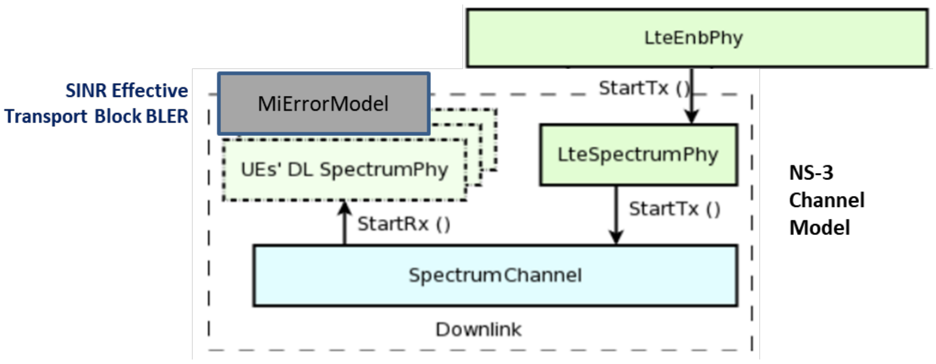

Figure 12. NS-3 Channel Model implementation and downlink transmission/reception.

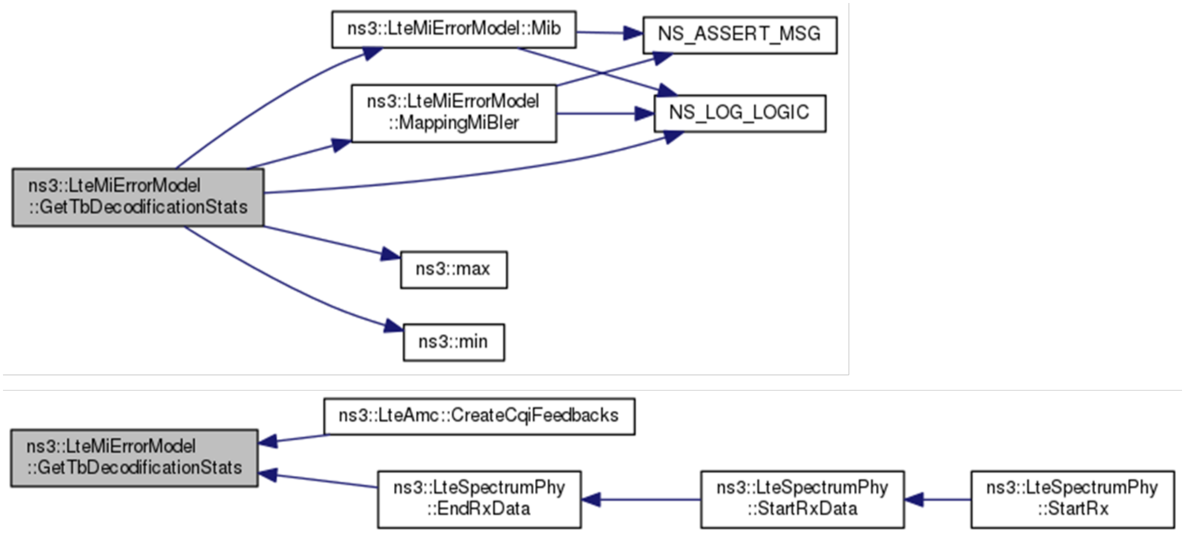

Figure 13. NS-3 Channel Model classes `LteSpectrumPhy` and `LteMiErrorModel` responsible channel model data transmission and reception and error model.

The main classes related to the PDSCH reception and error model process are the Channel Model classes `LteSpectrumPhy`, that is responsible for data transmission and reception, and for LTE PHY layer case, the `LteMiErrorModel` is responsible for error model.

As the Figure 13 shows, the Dowlink UE reception includes the `LteSpectrumPhy::StartRxData` and `LteSpectrumPhy::EndRxData`. This last trigger the CQI calculation and Error Model evaluation. The methods included in `LteMiErrorModel`, in case of LTE PHY layer case are:

`LteMiErrorModel::Mib`

> Provides the mean mutual information per bit, correspondent to the perceived sinr values in the whole bandwidth in Watt, the active RBs for the TB, and the MCS of the TB.

`LteMiErrorModel::MappingMiBler`

Provides the CB error rate based on mean mutual information per bit of a CB, Effective Code Rate ID, and the CB size.

`LteMiErrorModel::GetTbDecodificationStats`

Returns the TB error rate and MI based on the perceived sinr values in the whole bandwidth in Watt, the active RBs for the TB, the size in bytes of the TB, and the MCS of the TB.

`LteMiErrorModel::GetPcfichPdcchError`

This is related to the PCFICH+PDCCH channels that is not part of 5G-RANGE error model simulation.

The `LteMiErrorModel::MappingMiBler` calculates the CB error, and for that, Gaussian cumulative method is used for approximating the AWGN BLER curves with three parameters which provides a close fit to the standard AWGN performances, based on the mutual information (or *SINReff*) of the TB, bECR represents the "transition center" and cECR is related to the "transition width" of the Gaussian cumulative distribution for each Effective Code Rate (ECR) for limited 9 numbers of CB sizes. The proposal is that this method using ECR tables, can be replaced by using BLER x SINR curves for the 5G-RANGE CB sizes.

Within the `LteMiErrorModel::Mib`, the MIESM L2S mapping function in NS-3, is provided by Vienna MATLAB simulations, and in the 5G-RANGE EESM implementation, the proposal is to implement it in the NS-3 code.

The proposal to implement SINR compression using EESM is to create a new class `5gRangeErrorModel` based on the `LteMiErrorModel`. The changes in the methods are the following:

`5gRangeErrorModel::Mib`

Based on `LteMiErrorModel::Mib`, it provides the $SINR_{eff}$ using equation [1] for SINRi of N received TB.

Input parameters: N; SINRi; β parameter as a calibration factor.

`5gRangeErrorModel::MappingExpBler`

Based on `LteMiErrorModel::MappingMiBler`, it provides the CBLERi $SINR_{eff}$.

Input parameters: BLER x SINR for 5G-RANGE CBsizes and MCSs; CBsizes; MCS.

`5gRangeErrorModel::GetTbDecodificationStats`

Based on `LteMiErrorModel::GetTbDecodificationStats`, it provides the TBLER as defined in this section.

Input parameters: CBLERi.

3.5.2 CQI and MCS

The Adaptive Modulation and Coding (AMC) model already implemented to the LTE module handles the Modulation and Coding Scheme (MCS) calculation to define the PHY layer configuration for user data transmission Downlink and Uplink, and this will be extended to the 5G-RANGE simulator. There are two MCSs, one for Downlink and other for Uplink, and Figure 14 shows the gNB process to obtain the MCS for both cases.

For downlink, the gNB derives the MCS based on CQI feedback provided by the UE, and this MCS information is carried by using DCI0 to be used by the UE for user data Uplink transmission. For Uplink, the gNB derives the MCS based on Uplink signal quality measurement, and this MCS information is carried by using one of the DCI along with UE user data downlink transmission.

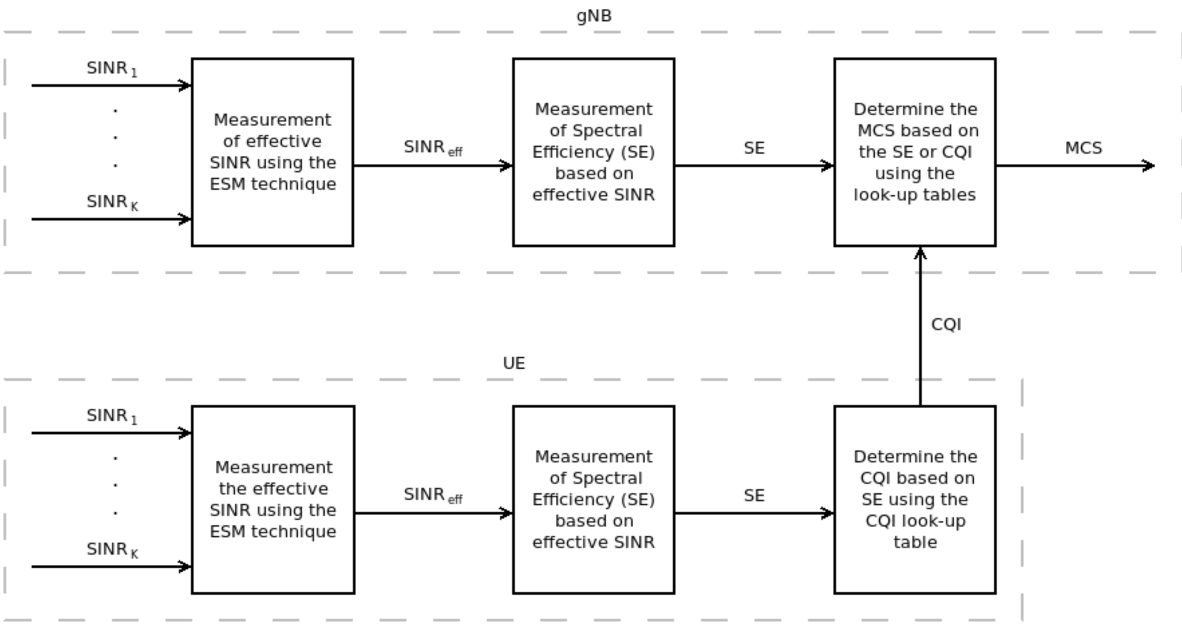

Figure 14. 5G-RANGE AMC Process.

In the NS-3 model, the Spectral Efficiency is measured to define both, CQI and MCS. Let *i* denote the generic user and let γ_i be its *SINR*. In the original LTE Module in NS-3, the spectral efficiency η_i of user *i* is gotten using the following

$$BER = 0.00005$$

$$\Gamma = -\ln\frac{5\times BER}{1.5}$$

$$\eta_{i=\log_2\left(1+\frac{\gamma_i}{\Gamma}\right)}.$$

The UEs derives the CQI value using reference signal (RS) SINR information, mapping spectral efficiency (SE) to CQI values provided by PHY information table. The gNB measures the Sound Reference Signals (SRSs) received, with a SINR value and it uses above expressions to map SE to MCS values.

NS-3 requires 5G-RANGE PHY layer tables of SE, Code Rate, Modulation for each CQIs values, and also tables of SE, Code Rate, Modulation for each MCS (see Table 3). Both tables for different numerologies. These tables are used by the `LteUePhy` e `LteEnbPhy` classes, inside the methods, for Downlink `LteUePhy::GenerateMixedCqiReport` and `LteUePhy::GenerateCtrlCqiReport`, and for Uplink `LteEnbPhy::GenerateDataCqiReport` and `LteEnbPhy::GenerateCtrlCqiReport`. Both methods also handle the Resource Block Group configuration wideband or sub-band. These methods invoke the `LteAmc::CreateCqiFeedbacks` where the MCS is calculated, and this is used on the `LteMiErrorModel`.

3.5.3 HARQ and Control Channel

5G-RANGE LLS does not consider hybrid automatic request (HARQ), requiring disabling the NS-3 HARQ implementation. Also, the control channel is considered to use a licenced spectrum with no error, requiring disabling the error model running on the control channel.

3.6 Numerical Results

In order to meet the requirements of the wide range of scenarios covered by the 5G-RANGE system [6], a new set of MCSs is proposed to adjust the transmission parameters and offer support from low-rate high-reliability communications – suitable, e.g., to the high-speed numerologies 4 and 5 with speeds up to 120 km/h and 240 km/h, respectively, to long distance communication links, and to the high-speed use cases such as the Remote Health Care (Multimedia) – up to low-redundancy high-rate communications – suitable, e.g., to low-speed numerologies 0 and 1 with speeds from 0 km/h to 30 km/h, and to low-mobility use cases such as Wireless Backhaul and Remote Health Care (Multimedia) [6]. The different numerologies defined for the 5G-RANGE system have been detailed in [5].

5G-RANGE then considers a total of 27 MCSs. The MCS indices, modulation order, spectral efficiency, and coding rate of those MCSs are presented in Table 3 below.

Table 3. Modulation and Coding Schemes of 5G-RANGE.

MCS	Modulation	Code Rate	Spectral Efficiency
0	out of range		
1	4	1/24	0.083
2	4	1/12	0.167
3	4	1/8	0.250
4	4	1/6	0.333
5	4	5/24	0.417
6	4	7/24	0.583
7	4	3/8	0.750
8	16	5/24	0.833
9	16	1/4	1.000
10	16	7/24	1.166
11	16	3/8	1.500
12	16	11/24	1.833
13	16	13/24	2.167
14	16	5/8	2.500
15	16	3/4	3.000
16	16	5/6	3.333
17	64	7/12	3.500
18	64	2/3	4.000
19	64	3/4	4.500
20	64	19/24	4.750
21	64	7/8	5.250
22	64	11/12	5.500
23	256	3/4	6.000
24	256	5/6	6.667
25	256	7/8	7.000
26	256	11/12	7.333
27	256	23/24	7.667

Also, the number of modulated symbols that can be transmitted in each RB in the 5G-RANGE sub-frame depends on the adopted numerology, which defines the number of subcarriers and GFDM symbols that compose such a block. Moreover, the number of RBs required to transport a single polar code block size also varies according to that code block size. Table 4 shows the number of REs and the number of RBs required to transport a coded block for the different numerologies and coded block sizes considered in 5G-RANGE.

As it can be noted in Table 4, for most of the coded block sizes in 5G-RANGE, a single RB can transport a whole coded block. Thus, as previously mentioned, the L2S to be considered in many of the cases might consider a single SNR sample to estimate the BLER. In such cases, a look up table for each configuration of interest might be simply directly embedded into the 5G-RANGE SLS.

Table 4. Number of required RBs for the different block sizes and numerologies.

Block Size	Modulation	Number of required RBs		
		# REs = 672 (Num. 0)	# REs = 720 (Num. 1-4)	# REs = 736 (Num. 5)
256	QPSK	1	1	1
	16-QAM	1	1	1
	64-QAM	1	1	1
	256-QAM	1	1	1
512	QPSK	1	1	1
	16-QAM	1	1	1
	64-QAM	1	1	1
	256-QAM	1	1	1
1024	QPSK	1	1	1
	16-QAM	1	1	1
	64-QAM	1	1	1
	256-QAM	1	1	1
2048	QPSK	2	2	2
	16-QAM	1	1	1
	64-QAM	1	1	1
	256-QAM	1	1	1
4096	QPSK	4	3	3
	16-QAM	2	2	2
	64-QAM	2	1	1
	256-QAM	1	1	1
8192	QPSK	7	6	6
	16-QAM	4	3	3
	64-QAM	3	2	2
	256-QAM	2	2	2

In the remaining cases, for example, block size 2948 and numerology 0, for QPSK, the β (to calculate the $SINR_{eff}$) would need to be calculated over two RBs. Another example would be the block size of 8192 and modulation QPSK for numerologies 1-4, whereas the $SINR_{eff}$ is calculated over 6 samples.

The error rate curves for each MCS have been evaluated in a simulation campaign with the LLS for a single link with the AWGN and the 5G-RANGE channel models and for code block (CB) sizes of 256, 512, 1024, 2048, 4096, and 8192 bits. Furthermore, curves to SISO, MIMO 2x2 and MIMO 4x4 antenna schemes need to be provided, considering the concept of numerology used in the 5G-RANGE system.

In order to illustrate the BLER results with SNR for the different MCSs proposed in Table 3 and block sizes depicted in Table 4, and also considering the numerologies proposed in D3.2 [5], three results are presented. These results are for AWGN channel (where the speed has no influence) and for the proposed channel models in D3.1 [1], namely the CDL_A, i.e., without LoS, and CDL_D, i.e., with LoS. Some remarks can be drawn:

- The MCSs' table gives well-spaced MCSs for the considered SNR range.
- The SNR starts before -10dB, which allows the user device (in a real system) to have service even when the channel conditions are very bad by providing a robust MCS.
- The behavior of CDL_D model is very similar to the AWGN, which is expected, since the LoS ray carries almost all the energy of the link compared to the other rays that generate the channel impulse response.

- As the speed increases, namely in the CDL_A model, a kind of plateau appears for higher SNRs, which is expected. For higher SNRs, the MCSs are also higher, i.e., the modulation and coding schemes are less robust to the channel variations. Therefore, if the channel becomes bad due to the high speed, the BLER cannot be less than a certain value.

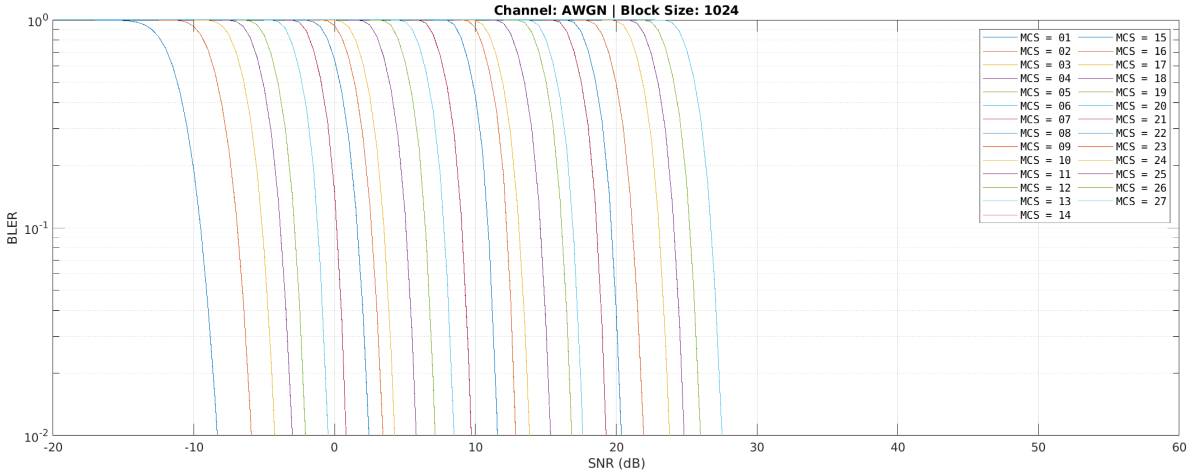

Figure 15. BLER curves for different MCSs. AWGN channel model and block size 1024.

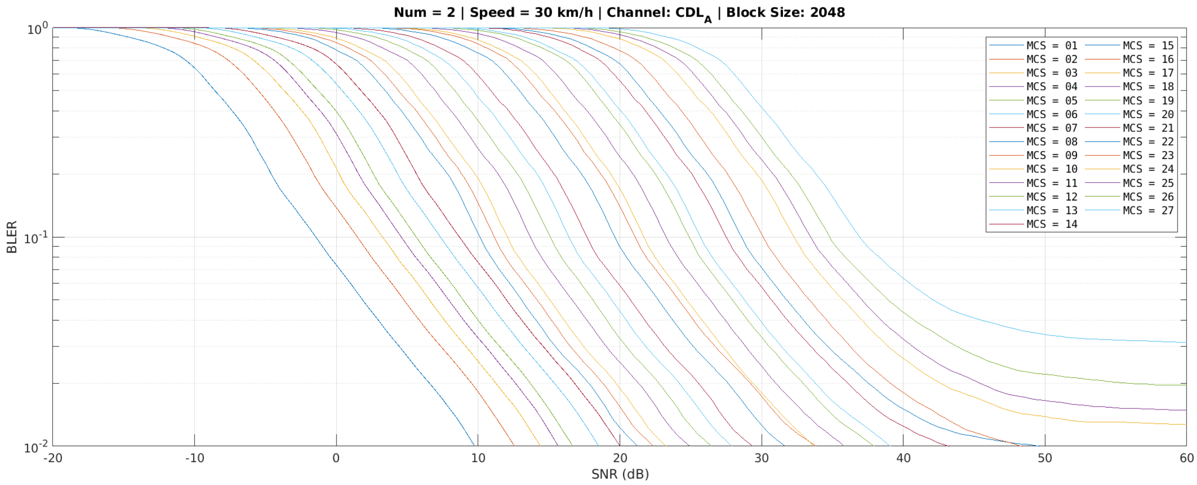

Figure 16. BLER for numerology 2, speed 30 km/h, CDL_A channel model, and block size 2048.

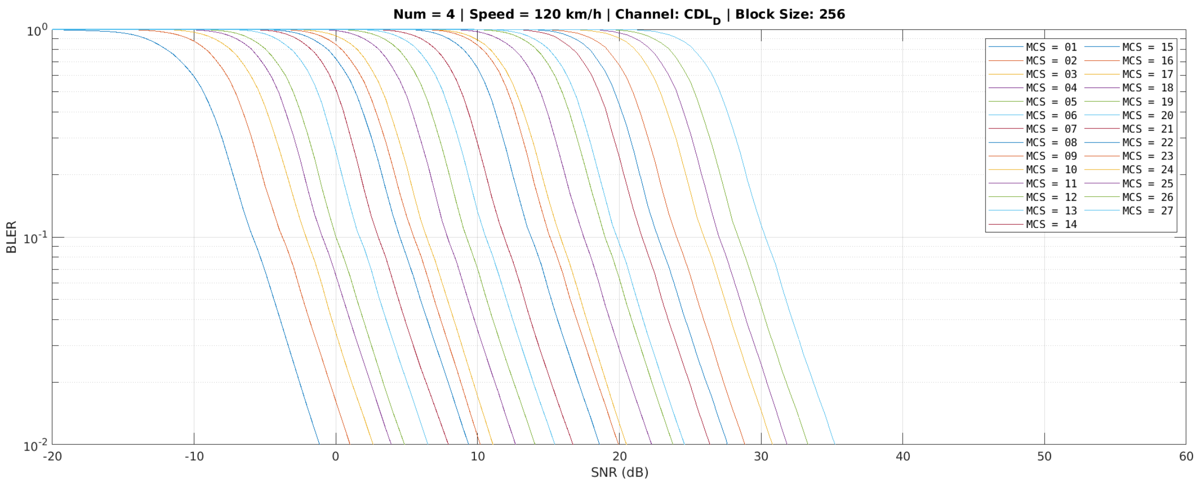

Figure 17. BLER for numerology 4, speed 120 km/h, CDL_D channel model, and block size 256.

In order to implement the EESM interface, the calibration process needs to determine the corresponding β values, as described in Section 3.2. For this purpose, each simulation of the calibration campaign has considered a large number of code blocks for different channel realizations, leading to more than 100,000 BLER measurements. As recommended in [12], BLER values in the range between 0.01 and 0.9 have been considered, since values outside this range are of no interest for training the model. The effective SINR has been calculated according to Section 3.2 and the β value has been optimized in order to minimize the Mean Square Error (MSE) between the actual BLER and the mapped BLER.

Table 5 presents the calculated β values, as well as the corresponding achieved BLER MSE, for a selected illustrative configuration. It has been verified that, in general, the order of the β values tends to increase for higher MCSs, as it is also the case in [12]. As previously mentioned, the EESM interface with the calculated β values could be used for the cases in which the number of RBs occupied by a CB is larger than 1, such as for a CB size of 8192 bits, as it has been shown in Table 4. Another option would be to directly use the simulated channel BLER curves, i.e. by mapping the averaged system level SINR directly to a BLER value using the curve corresponding to the current PHY parameters (MCS, CB size, scenario, etc.).

Table 5. EESM β calibration values and corresponding MSE for the following configuration: numerology 0, speed 0 km/h, CDL_D channel model, and block size 8192.

MCS	β	MSE
1	2.134	0.0312
2	1.828	0.0344
3	0.363	0.0343
4	0.246	0.0365
5	0.294	0.0349
6	0.484	0.0392
7	0.609	0.0384
8	0.761	0.0400
9	0.959	0.0402

MCS	β	MSE
15	7.049	0.0431
16	9.704	0.0421
17	15.428	0.0376
18	17.319	0.0392
19	35.034	0.0380
20	31.014	0.0379
21	50.182	0.0382
22	60.627	0.0386
23	58.879	0.0332

10	1.398	0.0430	24	88.459	0.0342
11	1.796	0.0433	25	110.411	0.0345
12	2.009	0.0425	26	152.814	0.0332
13	3.604	0.0459	27	209.301	0.0321
14	5.737	0.0426			

Figure 18 presents the calibrated curves for the same scenario considered in Table 5. The solid lines correspond to the AWGN curves and the dots correspond to the mapped values for the simulated blocks. The EESM interface fits the curves by minimizing the BLER MSE, which in this case is impacted by the different slopes of the AWGN and channel curves. The performance could be slightly improved if the EESM interface considered two calibration parameters, α and β, as in [3] and [12].

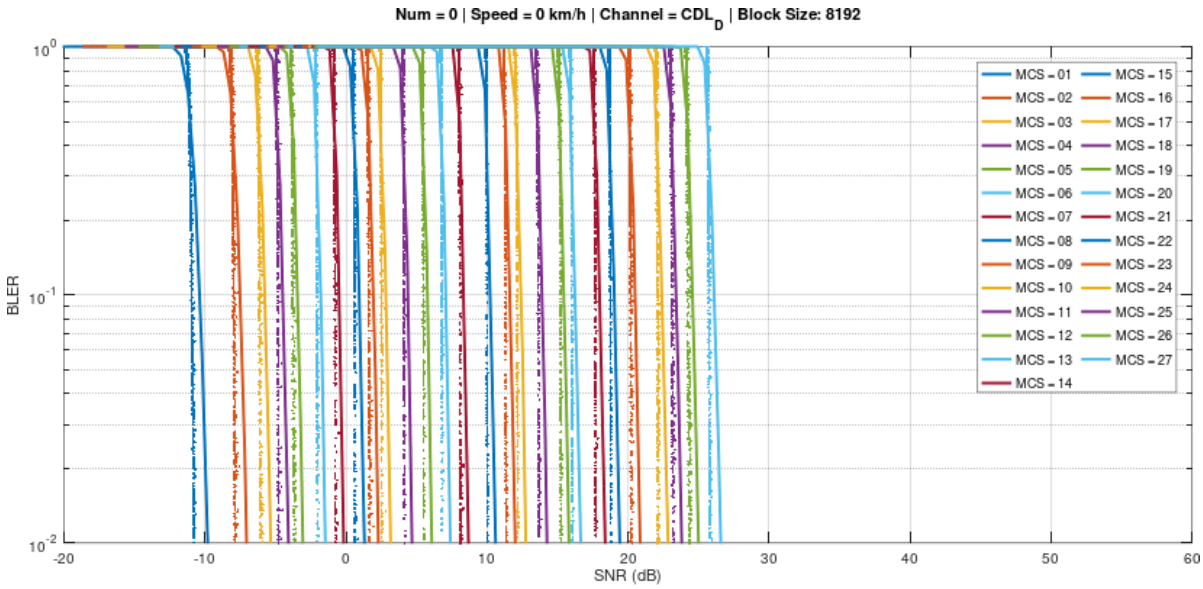

Figure 18. BLER for the AWGN scenario and corresponding calibrated points using the EESM interface for the configuration: numerology 0, speed 0 km/h, CDL_D channel model, and block size 8192.

Notice that, according to the data presented in Table 4, in more than 2/3 of the cases, only a single SINR measurement in an RB is present for each CB size, which would thus not require the usage of the EESM interface. Moreover, considering the facts that, inherently, the AWGN and the CDL_A and CDL_D curves have different slopes (diversity order) cf. Figure 15 and

Figure 17, and that for certain numerologies and associated speeds the BLER curves present an error floor cf. Figure 16, the accuracy of the BLER estimates based on average SNR values is expected to be higher if such SINR values are mapped directly to their respective BLER values using the corresponding SINR x BLER curves. While this approach might require additional memory to store the look-up tables, the complexity of the process shall be reduced to a simple search of the desired value in the respective look-up table.

4 Next Steps towards Final Demonstration

5G-RANGE network is a complex new operational mode for 5G to provide long-range coverage in remote and rural areas. As can be seen in Sections 2 and 3, this network is composed by several new PHY and MAC blocks to support different applications, varying from fixed and mobile broadband Internet access to IoT applied for agribusiness.

The proposed network relies on dynamic spectrum allocation (DSA) of TV white spaces (TVWS) for reducing the operational costs with spectrum licenses. This approaches requires several features, such as, geolocation databank access for available spectrum information, spectrum sensing for detecting unauthorized transmissions and signals present in a given region due unexpected propagation mechanisms, device-to-device (D2D) based on relays to support long-range uplink from mobile devices, efficient multiple access to accommodate human-driven and machine-driven data flows and mechanism for connecting the 5G-RANGE BS to the operator's core networks.

All these functions are required for commercial operation, but they might not be needed in a PoC demonstration. Due to resource restriction in the project, only the main 5G-RANGE features will be implemented for the final demonstration. The main features that will be available in the PoC are:

Waveforms: different waveforms will be implemented for real time operation. Generalized Frequency Division Multiplexing (GFDM) and Orthogonal Frequency Division Multiplexing (OFDM) will be available for selection. Windowing can be applied to all waveforms for reducing the out-of-band emissions (OOBE).

Channel Coding: Polar code has been selected as the channel coding scheme for 5G-RANGE. Several code rates will be available and rate adaptation will be implemented. Shortening, Padding and Puncturing can be used to adjust the data rate at the encoder's output.

Frame structure: the frame structure will consider at least two users. Control channel for reporting the spectrum sensing measurements will also be available. It is assumed that the UEs knows which channels are being used by the BS.

Bandwidth: 24 MHz composed by 4 Brazilian TV channels or 3 European TV channels will be considered. A test primary TV station might occupy one the downlink channels only. Maximum data rate of 100 Mbps is expected to be achieved when the 24 MHz bandwidth is available.

Numerologies: different number of subcarriers, subsymbols and cyclic prefix length will be available for addressing the requirements from different applications. However, the numerology cannot be dynamically changed during the demonstration. In order to change the numerology, the BS must be reset and new connections must be established manually.

MIMO: the 5G-RANGE frame has been designed to support multiple-input multiple-output (MIMO) schemes up to 4x4. However, due to hardware limitations, only MIMO 2x2 will be available in the PoC. The antennas can be used to achieve higher robustness against channel impairments (diversity) or higher throughput (multiplexing).

Adaptive Coding Modulation: the modulation order and coding rate will be dynamically adjusted in the downlink based in performance metrics available at the receiver.

Next, the field demonstration will be described.

4.1 Field demonstration

The main goal of the field demonstration is to show that 5G-RANGE network is able to surpass the restriction presented by current technologies. Standards available in the market today are able to offer a given level of connectivity, but they lack the ability to provide good user experience in remote areas.

There is no direct competitor with 5G-RANGE in terms of operational costs and quality of service for the final users. Some technologies that can partially address the demand in remote areas are:

Wi-FI: designed to be an indoor wireless network, Wi-FI has been used by small Internet providers to provide fixed wireless connectivity in remote areas. High power wireless routers with directive antennas use ISM bands (typically 2,4 GHz band) to cover large distance. However, Wi-FI cannot handle a large number of connected devices and interferences with other wireless networks leads to poor performance. New standards, such as IEEE 802.11af and IEEE802.11ah aim at using cognitive radio engines for exploiting TVWS. However, these new standards focus on low power transmissions (20 dBm) and short range.

IEEE 802.22: this is considered the first standard to employ cognitive radio technology. However, its PHY is heavily based on WiMAX and it employs OFDM as air interface. The high OOBE from this waveform requires RF filtering, hindering the possibility to change the spectrum when a primary user is detected. Also, the few practical implementations of this standard purely rely on geolocation database and does not use spectrum sensing, meaning that unauthorized transmissions cannot be detected.

LORA: this standard has been designed for low throughput machine-type communication (MTC) application and it cannot provide Internet access. It can achieve large coverage, but at very low data rates. Round trip latency is around 1~2 seconds, which means that this solution cannot be used for mission critical MTC applications. LORA can be combined with 5G-RANGE to provide IoT services in remote areas. In this case, 5G-RANGE can be used as a backhaul link for the LORA BS.

SIGFOX: this is a closed standard designed for MTC applications. It can achieve up to 50 km coverage, but only few bytes can be transmitted. SIGFOX cannot be used for Internet access, but it can be combined with 5G-RANGE for providing IoT services in remote areas. In this case, 5G-RANGE will provide the backhaul for the SIGFOX BS.

LTE Advanced and NB-IoT: 5G-RANGE can be seen as an evolution of 3GPP Release 14, once it can achieve much larger coverage (50 km vs. 10 km) and provide higher data rates (100 Mbps vs. 20 Mbps) at the cell edge. 5G-RANGE frame also supports a numerology for IoT devices, as NB-IoT. But 5G-RANGE higher flexibility can be exploited to support IoT applications that also requires high data rates, such as video surveillance, drone image capturing and camera monitoring in remote/rural areas.

The field demonstration will cover three use cases defined in D2.1, which are Voice and Data Connectivity, Smart Farm and Wireless Backhaul. All use cases will be demonstrated in a rural property in Santa Rita do Sapucaí, MG. The 5G-RANGE BS will be installed in a tower located in the vicinities of the city and the two UEs will be installed in the farm.

For the voice connection demonstration, one UE will be able to perform a voice over IP call to the other UE without using the Internet connection, which means that the voice connection between the users will be handle by the 5G-RANGE Network layer. Figure 19 depicts this user case.

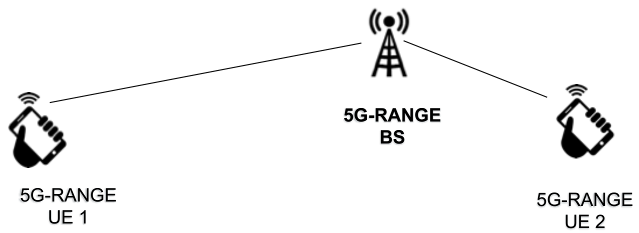

Figure 19. Voice connectivity use case.

For the data connectivity demonstration, the two 5G-RANGE UEs will simultaneously access YouTube videos and Internet webpages. A satellite or optical link will be used as backhaul for the 5G-RANGE BS, as shown in Figure 20.

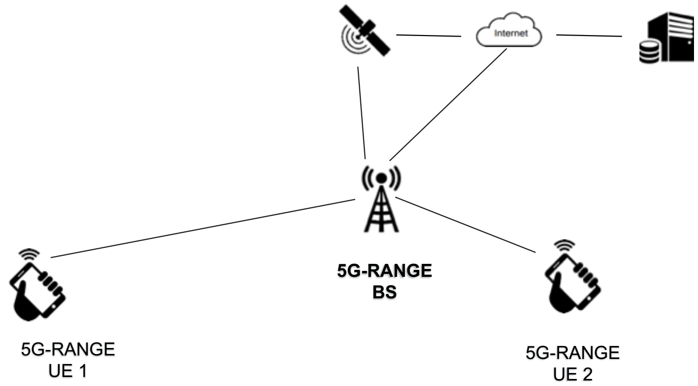

Figure 20. Data connectivity use case.

The Smart Farm and Backhaul use cases will be performed jointly. In this case, 5G-RANGE UE 1 will provide backhaul access for a Wi-FI router that will distribute the Internet access link locally among several devices. 5G-RANGE UE 2 will provide backhaul access to a LORA gateway. IoT devices will be deployed in the farm to measure soil humidity and pH, and air temperature. Sensors will also collect data from cows. Actuators will be used for watering system and drones will forward images to a server. Figure 21 depicts the scenario for the Smart Farm and Backhaul use cases.

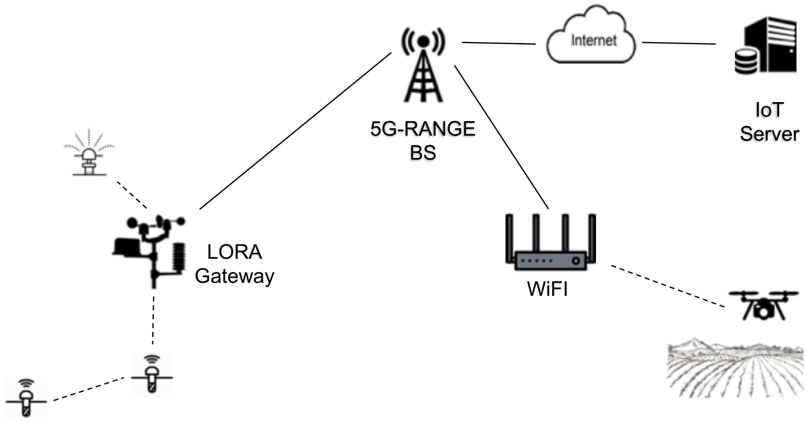

Figure 21. Backhaul and Smart Farm use cases.

In all demonstrations, an experimental TV station will be used to analyze the performance of the CMAC. The TV signal will be intermittently transmitted in one of the channels used in the downlink. The UE devices will report the presence of the signal to the BS and the subcarriers allocated in the channel occupied by the TV signal will be turn off. A digital TV analyzer will be used to measure the impact of the 5G-RANGE signal in the TV reception and the measurement tools implemented in the 5G-RANGE UEs will analyze the impact of the TV signal in the 5G-RANGE performance.

The foreseen 5G-RANGE demonstrations will show that the proposed network can be used to provide reliable services in remote areas, supporting applications from different classes. By providing high data rate Internet access and reliable connection in remote area, 5G-RANGE final field demonstration will show that the connectivity gap between cities and rural/remote areas can be closed.

5 TRL

The 5G-RANGE network is composed by several blocks in the PHY, MAC and Network layers that are being designed to address the requirements listed in D2.1. Besides the scientific contributions, this project also aims for providing significant contributions for the industry and operators. The current version of the PoC uses a National Instruments platform based on USRP 2954 and LabView Communication. All PHY blocks are running in FPGA and can be easily migrated for third parties' platforms, which facilitates transferring the technology to the industry. Figure 22 shows a picture of the current version of the PoC.

Figure 22. PoC based on National Instruments platform.

Today, low cost telecommunication infrastructure equipment is being implemented in software to be executed in GPP. This approach reduces the costs of the equipment and also allows evolution via software updates. Software designed radio (SDR) follows this strategy and brings more flexibility for the product development. Hence, the 5G-RANGE project members are focusing efforts to implement major PHY, MAC and Network blocks in software. Current generation of GPPs is able to provide more than 100 Mbps throughput and small SDR interfaces can generate and receive broadband wireless signals. The softwarization of the MAC and PHY components also helps transferring the technologies and solutions developed in the 5G-RANGE. Some PHY blocks demand high level of parallelism to provide high throughput. The main example is the Polar decoder and the MIMO demultiplexing. In these cases, the software implementation would lead to a bottleneck in the system data rate. Therefore, the new platform will rely on an FPGA accelerator to perform timing critical tasks. Figure 23 presents the architecture of the new platform while Figure 24 presents a picture of the next version of the PoC.

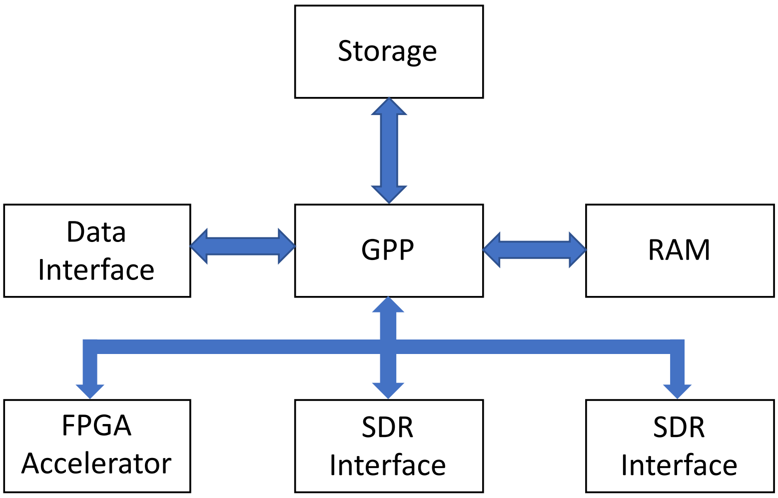

Figure 23. Architecture of the SDR-based platform.

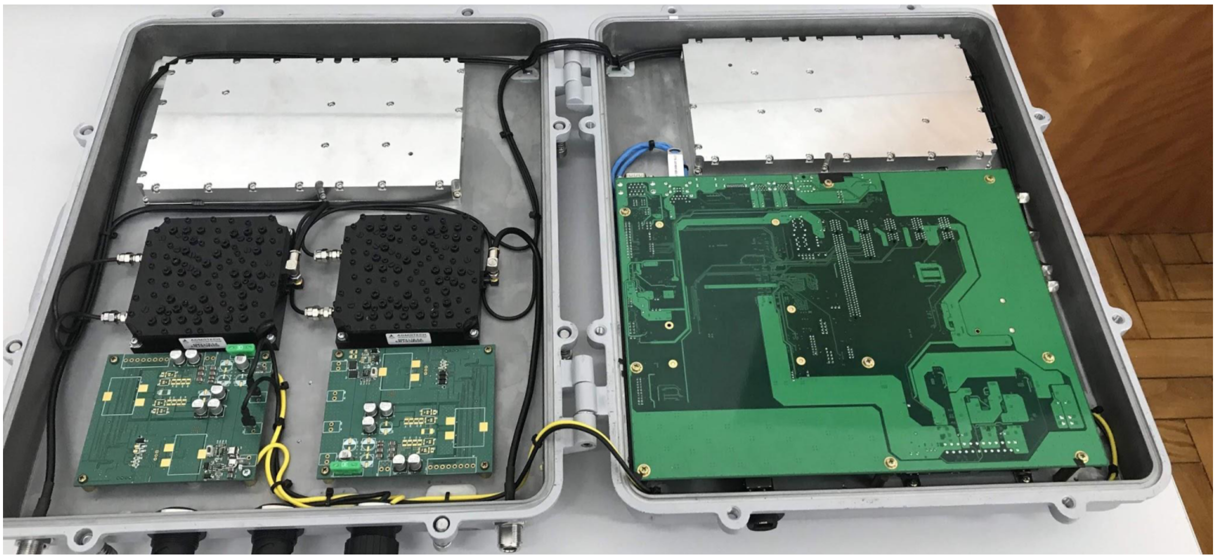

Figure 24. Next version of the PoC.

presents the expected TRL for the main blocks designed in the 5G-RANGE project and also for the BS and UEs.

Table 6. TRL for the 5G-RANGE components and systems.

Block	Description	TRL
5G-MIMORA	MIMO system for remote area operation, covering diversity and multiplexing modes.	6
5G-ACRA	Channel coding scheme, including encoder, decoder and rate adaptation.	6
5G-FlexNOW	Waveform generator and detector for OFDM, GFDM and F-OFDM.	6
5G-IR2A	Algorithms for synchronization, channel estimation and gain control.	6
5G-FRAMER	Flexible frame multiplexer and demultiplexer for different operation modes.	6

5G-COSORA	Cooperative spectrum sensing scheme, including the reporting channel.	5
5G-DARA	Dynamic spectrum access scheme for fragmented spectrum allocation.	5
5G-D2DRC	Device to device communication for the 5G-RANGE uplink.	3
5G-RANGE BS	Base station for the PoC.	5
5G-RANGE UE	User equipment for the PoC.	5

6 Conclusions

The network proposed by the 5G-RANGE project is focused on provide reliable connectivity in remote areas for different verticals. A large number of use cases in remote areas can be addressed by the 5G-RANGE network. However, due to resources limitations, only the main network features will be implemented in the PoC. The system simulator described in this document has been implemented to overcome this limitation, allowing one to fully exploit the potential of the proposed network.

The flexible PHY composed by innovative waveform, powerful channel codes and MIMO arrays has been simulated under different channel models, resulting into a large set of performance curves. These curves are used to feed a cognitive MAC simulator, abstracting the PHY and increasing the simulation performance without loss of generality. The cognitive MAC layer has been developed using a high level opensource simulation platform. The new blocks designed for the 5G-RANGE cognitive MAC have been integrated into conventional MAC available in the simulation platform, allowing other researchers and professionals to use the outcome of this project.

The system simulator will also be employed as a reference design for the PoC. In fact, since the PoC will be implemented using SDR technique, several functions developed for the system simulator can be used in the PoC as well. This approach will increase the flexibility of the PoC, which will be used to demonstrate three use cases defined in D2.1. The PoC will also be used for the coverage survey in order to estimate the overall system performance in the field. Throughput measurements at different distances from the BS, up to 50 km, will be conducted in Santa Rita do Sapucaí.

The SDR approach for the PoC implementation will lead to a BS prototype with higher TRL. Since the main Network, MAC and PHY functions will run in a GPP, the SDR solution developed by Inatel for the telecommunication industry will also be used for the 5G-RANGE PoC, resulting in close-to-the-market solution that can be easily transfer to the industry.

References

[1] 5G-RANGE, “Deliverable 3.1 Physical layer of the 5G-RANGE – Part I,” December 2018.

[2] J. C. Ikuno, M. Wrulich, M. Rupp, “System level simulation of LTE networks,” in Proc. IEEE Vehicular Technology Conference, pp. 1-5, May 2010.

[3] E. M. G. Stancanelli, C. H. M. Lima, and D. C. Moreira, “Strategies for Link-Level Performance Assessment in the Simulation of Wireless Systems,” in Optimizing Wireless Communication Systems, F. R. P. Cavalcanti, S. Andersson, Ed. Springer, 2009, pp. 269-309.

[4] M. of WINNER, “Assessment of advanced beamforming and MIMO technologies”, WINNER, Tech. Rep. IST-2003-507581, 2005.

[5] 5G-RANGE, “Deliverable 3.2 Physical layer of the 5G-RANGE – Part II,” February 2019.

[6] 5G-RANGE, “Deliverable 2.1 Application and requirements report,” April 2018.

[7] Anthony, Faustine, Maria Gabriel, and Bertha Shao. "Open source cellular technologies for cost effective cellular connectivity in rural areas." International Journal of Computer Applications 146.15 (2016).

[8] Bratu, Erin, and Bryan Harper. "Open Source Mobile Network Using OpenBTS and USRP 9." The University of Mississippi Undergraduate Research Journal 2.1 (2017): 12.

[9] Ericsson & Telstra - A, R1 - 166599, Measurements for extreme rural scenario, Göterberg, 2017.

[10] Ericsson & Telstra - B, R1-167451 Channel model for extreme rural scenario, Göteberg, 2016.

[11] Ericsson & Telstra - C, R1-167452 Path loss model for extreme rural scenario, Göteborg, 2016.

[12] J. Olmos, S. Ruiz, M. García-Lozano, D. Martín-Sacristán, “Link abstraction models based on mutual information for LTE downlink,” COST 2100 TD. 10, pp. 1-18, Jun. 2010.