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Lead editors	Klaus Moessner & Haeyoung Lee (UNIS)
Authors	Benoit Miscopein, Rida El Chall (CEA); Bismark Okyere (Intel); Klaus Moessner, Haeyoung Lee, Marcin Filo, Seiamak Vahid (UNIS),Salva Díaz, Oscar Carrasco, Federico Miatton (Sistelbanda)
Reviewers	Keith Briggs (BT), Valerio Frascolla (Intel), Anastasius Gavras (Eurescom)
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Abstract

One of the main research objectives of the SPEED-5G project is the development of a new MAC layer and associated framework which will facilitate efficient resource allocation across a number of heterogeneous radio access technologies. In addition, it will enable exploitation of FBMC technology to address resource fragmentation. The proposed framework enables flexible exploitation of radio resources and spectrum from different licensing regimes. This deliverable contains a detailed description of MAC strategies for small cells, which are capable of the efficient use of a range of bands having different characteristics.

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Executive Summary

SPEED-5G's main objective is to investigate and develop MAC/RRM technologies that address the well-known challenges associated with capacity demands in the 5G era, by addressing the lack of dynamic control across diverse wireless networks resources, leading to unbalanced traffic loads and capacity bottleneck. SPEED-5G has therefore defined the concept of enhanced dynamic spectrum access (eDSA) for the support of scenarios where a large number of small cells are able to access co-existing heterogeneous radio access technologies and heterogeneous spectrum bands (of different spectrum regimes) simultaneously.

This deliverable provides description of a novel MAC framework designed for, and adopted in, the SPEED-5G project. The main design innovations are:

1. Distribution of legacy MAC layer functionality into higher & lower MAC sublayers (where the higher-MAC sublayer is in charge of coexistence and coordination functions whilst the lower-MAC functions remain responsible for real-time operations, such as scheduling.
2. Definition and specification of new internal SAPs and interfaces to enable communications between MAC, RRM, and higher protocol stack layers.
3. Development and specification of a new monitoring and sensing plane independent of legacy control/data/management planes, for flexible and efficient collection of QoS-related measurements and spectrum-sensing results collection.
4. Support of RAN virtualization through the framework capable of accommodating different c-RAN functional split options across different layers.
5. Native multi-RAT and multi-channel operation support.

The high-level MAC functions support simultaneous management of contention-based and non-contention-based random access control to enable better exploitation of available licensed, lightly-licensed, and unlicensed spectrum resources based on multi-RAT coordination mechanisms. Although the proposed framework is able to support different underlying PHY-layer designs and waveforms, for the access to non-contiguous spectrum from multiple bands of different regimes, FBMC (Filter Bank Multicarrier) which is robust to synchronization errors, is selected for the physical layer and tightly coupled to a MAC design supported by the SPEED-5G MAC framework.

The proposed MAC framework consists of control, data, and monitoring interfaces; and building blocks and service access points. A number of MAC protocols have been developed which can exploit the flexibility and scalability of the proposed framework under the various spectrum regimes. In addition, to cope with the cases where the small cells cannot fully exploit the capabilities of the virtualized architecture, for example due to poor quality of backhaul links which do not allow for information exchange in a timely manner, one of the proposed MAC designs (specifically DCS-MAC) has been developed to support operation in more autonomous manner, meaning that it is capable of adapting its behaviour based on locally obtained information.

This deliverable reports on the proposed MAC framework, new MAC designs and the preliminary performance evaluation results. More results under common simulation scenarios and assumptions, along with improved MAC protocols will be provided in the deliverable D5.2; future plans for MAC protocol evaluation and strategy selection are shared in this document.

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Abbreviations

ACK	Acknowledgement
ACL	Adjacent Channel Leakage
ACLR	Adjacent Channel Leakage Ratio
AIV	Air Interface Variant
A-MPDU	Aggregated-MAC PDU
A-MSDU	Aggregated-MAC SDU
AP	Access Point
BLER	Block Error Rate
BP	Beacon Period
BPSK	Binary Phase Shift Keying
BS	Base Station
ASA	Authorized Shared Access
CA	Carrier Aggregation
CAP	Contention Access Period
CAPEX	Capital Expenditure
CCA	Clear Channel Assessment
C-IoT	Cellular IoT
CoMP	Coordinated Multipoint
CP-OFDM	Cyclic Prefix based Orthogonal Frequency Division Multiplexing
CQI	Channel Quality Indicator
cRRM	Centralized RRM
CSAT	Carrier Sensing Adaptive Transmission
CSI	Channel State Information
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
cSON	centralized Self-Organizing Network (SON)
CTS	Clear To Send
D2D	Device-to-Device
DCI	Data Control Indicator
DFS	Dynamic Frequency Selection
DL	Downlink
DRX	Discontinuous Reception
DSA	Dynamic Spectrum Access
DTP	Data Transfer Period

ED	Energy Detection
eDSA	extended Dynamic Spectrum Access
eMBB	Extreme Mobile Broadband
eNB	eNodeB
ER	Exception Report
FBMC	Filter Bank Multicarrier
FFT	Fast Fourier Transform
FS-FBMC	Frequency Spreading-FBMC
GBR	Guaranteed Bit Rate
GTP	GPRS Tunnelling Protocol
HARQ	Hybrid Automatic Repeat Request
HeNB	Home eNodeB
HeMS	HeNB Management System
HetNet	Heterogeneous Network
HO	Handover
I/O	Input and Output
IoT	Internet of Thing
IPSec	Internet Protocol Security
KPI	Key Performance Indicator
LAA	Licensed Assisted Access
LBT	Listen Before Talk
LTE-U	LTE-Unlicensed
LUT	Lookup Table
LWA	LTE/WLAN link aggregation
MAC	Medium Access Control
MAR	Mobile Autonomous Reporting
MAS	Medium Access Slot
MCS	Modulation and Coding Scheme
MIMO	Multiple Input Multiple Output
mIoT	Massive Internet of Thing
MOCN	Multi-Operator Core Network
MPAP	Multi-Purpose Access Point
NC	Network Command
OAM&P	Operations, Administration, Maintenance and Provisioning
OFDM	Orthogonal Frequency Division Multiplexing

OPEX	Operational Expenditure
OQAM	Offset Quadrature Amplitude Modulation (QAM)
PAM	Pulse Amplitude Modulation
PAPR	Peak-to-Average Power Ratio
PDCP	Packet Data Convergence Protocol
PDU	Protocol Data Unit
PER	Packet Error Rate
PF	Proportional Fair
PHY	Physical Layer
PR	Periodic Report
QCI	QoS Class Identifier
QoE	Quality of Experience
QoS	Quality of Service
QPSK	Quadrature Phase Shift Keying
RA	Random Access
RACH	Random Access Channel
RAN	Radio Access Network
RAT	Radio Access Technology
RB	Resource Blocks
ReTx	Retransmission
RLC	Radio Link Control
RR	Round Robin
RRC	Radio Resource Control
RRM	Radio Resource Management
RTS	Request To Send
SAP	Service Access Point
SC	Small Cell
SCF	Small Cell Forum
SC-FDMA	Single Carrier FDMA
SDR	Software Defined Radio
SDU	Service Data Unit
SIMO	Single Input Multiple Output
SON	Self-Organizing Network
SRS	Sounding Reference Signal
TB	Transport Block

TCP	Transmission Control Protocol
TTI	Time Transmission Interval
TVWS	TV White Space
Tx	Transmission
UDN	Ultra-Dense Network
UFMC	Universal Filtered Multicarrier
UL	Uplink
URC	Ultra-Reliable Communication
WSN	Wireless Sensor Network

1 Introduction

SPEED-5G's main objective is to investigate technologies to consider the well-known challenges of growth in mobile connections and traffic volume by addressing the lack of dynamic control across wireless network resources, which is leading to unbalance spectrum loads and capacity bottleneck. In order to solve such problems, SPEED-5G focuses on extended dynamic spectrum access (eDSA) in the scenario where a large number of small cells (SCs) can operate across co-existing heterogeneous radio access technologies and use heterogeneous spectrum bands simultaneously.

This deliverable describes the medium access control (MAC) approach designed to support operation in, and exploitation of available spectrum resources in licensed, unlicensed, and lightly-licensed bands in dense deployment scenarios. In this regard, the MAC layer is as a component of the SPEED-5G virtualized protocol stack defined in [2]. In particular, the support of several radio access technologies (RATs) and the ability to combine several carriers in both uplink and downlink are key aspects of the SPEED-5G MAC layer. At stake in the system definition is the way MAC layer and radio resource management (RRM) functions interact, which is a key part of the SPEED-5G work. Indeed, it governs how the strategies of capacity maximization implemented in the RRM are translated into MAC configuration parameters, as well as what kinds of information are forwarded from MAC to RRM. It is worth noting that the MAC layer is assumed to be configured by the (virtualized) RRM algorithms but support for non-virtualized architectures is also provided. Indeed, in this situation, the MAC layer has limited support of the infrastructure; for example, due to poor quality of backhaul links, information may not be exchanged in a timely manner. This may lead to significant performance degradation unless a more autonomous decision-making system in MAC is selected as a fall-back configuration.

Another important part of the SPEED-5G project is the MAC layer support for the FBMC (Filter Bank Multicarrier) physical layer (PHY). Due to a sharp spectral localisation, the FBMC PHY shows extremely interesting features for the MAC design such as the ability to exploit fragmented spectrum or relaxed synchronization among multiple users. Thus, the MAC algorithms are designed with the assumption that the FBMC PHY is available and can be used on the various spectrum regimes including unlicensed spectrum where traffic can be efficiently offloaded.

The remainder of this deliverable is structured as follows: Chapter 2 discusses the MAC layer features and requirements for SPEED-5G at a high level as well as protocol stack vision and performance metrics. Chapter 3 presents the MAC framework and describes the functional blocks of the MAC layer supporting multi-RATs and multi-bands to implement the eDSA concept in SPEED-5G. The overall block diagram of the SPEED-5G MAC framework is included along with description of individual functions and interfaces between MAC and the neighbouring layers. Chapter 3 also presents the MAC architecture designed for SPEED-5G from both cell side and user side. In Chapter 4, three distinct MAC designs are presented that are enabled through the proposed MAC framework; the MAC algorithms can be operated with a FBMC PHY. The virtualized architecture defined in the project is also considered in designing the MAC framework and algorithms. In addition, a self-organizing MAC algorithm is proposed which is capable of operating autonomously without the information of spectrum characteristics to cover the case when the small cells cannot reply on the virtualized architecture. The preliminary results on all proposed MAC algorithms are included along with simulation parameters in Chapter 5. Finally, Chapter 6 elaborates on the conclusions of the deliverable and the next steps.

2 SPEED-5G MAC vision and performance metrics

As SPEED-5G addresses 5G design, it complies with the evolution/revolution paradigm of RAN design, adapted to the specific working assumptions of the project (dense heterogeneous networks, multi-RAT support and use of additional spectrum). This means that we can distinguish two approaches in SPEED-5G. The first approach aims at providing a means to improve the dual connectivity of LTE, either by coordinating LTE and Wifi more efficiently when operating in the 5 GHz band or by considering other frequency resources or waveforms, in an extended LAA concept. We consider FBMC modulation as our primary choice, taking advantage of the excellent spectral localisation of this waveform (discusssed lated on in the document). The second approach is more disruptive and permits more radical changes which aim at facilitating simultanous operation in multiple bands which might follow different licensing regimes, and at heterogeneous spectrum resource allocation. This new access will involve more distributed random access procedures, although being locally managed by a centralised coordination, so that interference can be natively managed. This more disruptive approach is aimed at facilitating the migration of network architectures.

2.1 SPEED-5G protocol stack vision

The key value of SPEED-5G is to support eDSA, and consequently the defined protocol stack has to be capable of managing multiple eDSA techniques simultaneously per band, and allocating the RAT in an optimal way. The goal of this section is to describe how the SPEEG-5G MAC layer can be managed by a protocol stack which is mapped onto a virtualized architecture, as reported in [2].

Figure 1 below represents the eDSA-capable protocol stack developed in the SPEED-5G project. The whole protocol stack is configured and managed by a virtualized centralized RRM (cRRM) entity which deals with multi-user, multi-cell and multi-connection network capacity through the coordination interface. The cRRM objective is the maximization of the system spectral efficiency, summed across the different available frequency bands. The proposed functional split is below the Packet Data Convergence Protocol (PDCP) level (in charge of both the control and data planes), potentially allowing for a common security framework for all the RATs of a cell, when supported.

In order to natively support carrier aggregation on different possible RATs, the user plane includes a Multi-Path-TCP layer, for scheduling TCP services over different radio bearers in parallel. These TCP paths are embedded in different GTP tunnels in order to redirect these services to one or more RATs of a cell or of multiple cells, in order to support Coordinated Multipoint (CoMP) and virtual multi-cell Multi Input Multi Output (MIMO) schemes. The control plane is handled by the 5G-RRC function which manages the control procedures of the supported RATs, applying the eDSA procedures coordinated at the cRRM level.

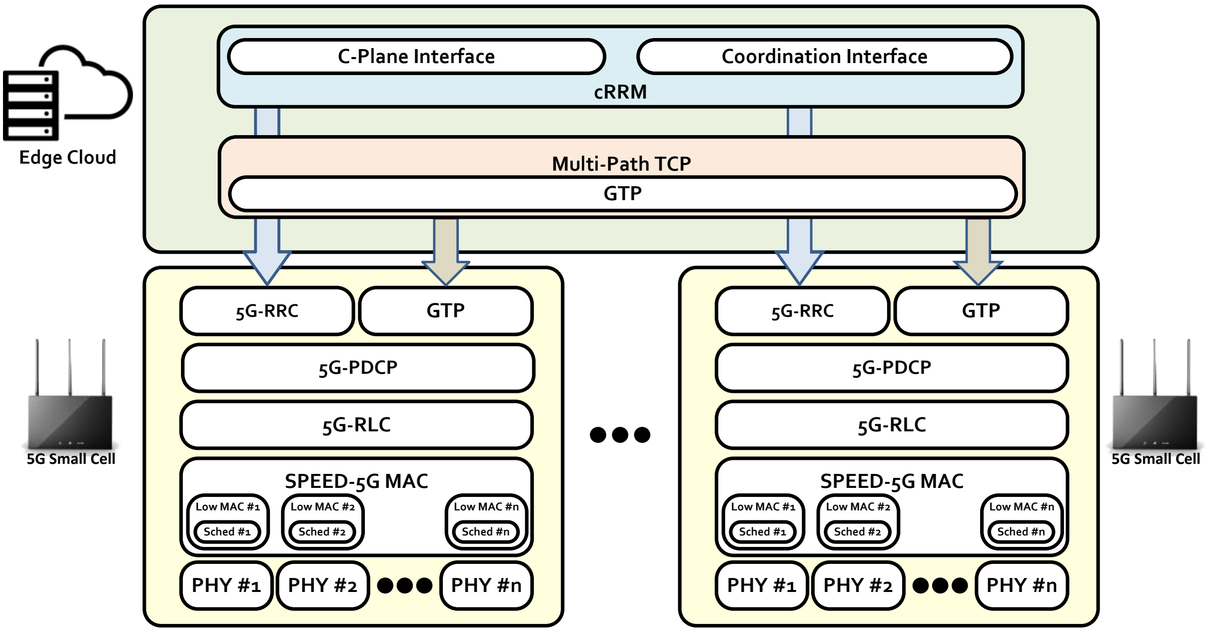

Figure 1: SPEED-5G MAC Layer from cell side

Figure 1 highlights how SPEED-5G MAC layer can handle multiple RATs and can be configured by the higher 5G-Radio Resource Control (RRC) layer. The proposed MAC layer includes several different instances or parallel threads (depending on the cell capabilities) of RAT-dependent MAC functions, such as the resource allocation scheduling algorithms, or the HARQ management. The main idea is to provide enough flexibility to add new RATs and provide backwards compatibility towards legacy RATs, such as LTE and WiFi. Each scheduler is not bound to a unique 5G-RLC logical channels, and it is important to note that a 5G-RLC instance can be potentially connected to different schedulers, for instance to an LTE and an LAA (Licensed Assisted Access) scheduler.

The MAC layer has to be highly flexible and scalable, and able to support different functional splits in the virtualisation process. The most suitable virtualization split for the air interface protocol stack actually depends on the physical fronthaul characteristics (available link capacities and delay constraints), which constitutes the most common bottlenecks in the recent architecture proposals. Depending on the stack deployment, the MAC may be virtualized or not. More details about this may be found at [4]. When the MAC is not virtualized, the deployed MAC contains the whole set of functions; that is, it is considered a self-contained MAC, and the centralized Radio Resource Management (cRRM) activates or deactivates MAC functions. In this case, flexibility is achieved by cRRM (re)configuration procedures. On the other hand, when the MAC is virtualized, additional flexibility is provided through the SDR paradigm that allows on-the-fly (re)configuration and placement of some functions of the protocol stack.

New requirements and services demand new functionalities on the MAC layer. The proposed SPEED-5G MAC framework is also able to support coexistence in order to properly execute eDSA. The channel coexistence is mainly for lightly licensed and unlicensed spectrum access, since the licensed spectrum is tightly regulated. For this reason, channel coexistence is mainly used for carrier aggregation over lightly licensed spectrum access or access to unlicensed bands. The channel coexistence functionality is responsible for triggering the scheduling procedure ensuring the seamless usage of shared resources. Considering current technologies as WiFi, channel coexistence is responsible for knowing when a new transmission has to be initiated. Then, using this module, compatibility with current technologies is ensured. Furthermore, the framework provides native support for Licensed Assisted Access (LAA) [43][44] as well as LTE-WLAN Access (LWA) [42].

Another important requirement is support for Multi-Operator Core Network (MOCN) [45] and multi-tenancy, where multiple mobile operators share small cell services, consequently also sharing the wireless resources. The proposed MAC supports this natively, since it has a scheduler per RAT and the scheduling policies are configurable. The wireless resources are finite and shared between operators, and for that reason, the network has to be capable of establishing fairness policies. How the scheduler is configured is out of scope for this deliverable. It is important to note that, some of the parameters of the eDSA techniques could be shared between operators as they are common to the cell. On the other hand, there are parameters which each operator may modify depending on its own criteria and operational requirements.

As depicted in Figure 1, the SPEED-5G MAC layer is foreseen to provide support for simultaneous operation of multiple RATs. In order to properly handle issues related with multi-RAT operation, SPEED-5G proposes to decompose MAC layer into two sublayers which we refer to as higher-MAC and lower-MAC. The higher-MAC is composed of a set of functions which do not require real-time execution and are not specific to any particular RAT. Their main aim is to coordinate and intelligently manage underlying Lower-MAC entities, applying the long-term cRRM decisions at the MAC level. The lower-MAC includes different RAT-specific functions (for example, KPI management, channel (de)multiplexing, and (de)framing) and functions which need to be executed in real-time, such as scheduling. In some way, higher-MAC can be seen as a convergence point of the protocol stack dealing with the control path, decoupled from the user plane and managing the sets of possible bearers. The introduction of higher-MAC intends to open a way for a native support of multi-connectivity, integration of innovative multiple access techniques and use of different forms of cross-RAT spectrum and carrier-aggregation techniques; that is, heterogeneous resource aggregation. It needs to be highlighted that in the proposed split in the MAC framework, the lower-MAC should not be considered a standalone MAC as it encapsulates just a subset of functions necessary for a standalone operation.

The following describes a list of SPEED-5G MAC features considered, which are intended to allow efficient operation of single-RAT and multi-RAT devices across different technology-specific and technology-neutral bands (licensed, lightly-licensed, or unlicensed):

- Common and dedicated control traffic is required for proper operation of every radio system. In order to take advantage of multiple RATs which may operate in different frequency bands, different licensing regimes and potentially offer different QoS, the SPEED-5G MAC facilitates coordination of control traffic transmission across multiple RATs. For instance, such coordination allows a device to convey time-critical control information for RATs operating in an overloaded unlicensed band using RATs operating in a licensed band, thus ensuring proper reception. In addition, depending on the number of users, channel conditions or existence of additional radio interfaces, the amount of control traffic which needs to be transmitted over the air may vary. Furthermore, resources allocated to control channels may experience different level of interference. In order to address these issues, the proposed MAC allows for adaptation of control channel configuration.
- Devices which support multiple RATs often have access to resources not available for single RAT devices. In order to fully exploit the availability of these resources, the SPEED-5G MAC framework manages distribution of load across different RATs. The load could be distributed based on various pieces of information such as channel load, traffic QoS requirements, or retransmission status. Such a feature would also facilitate a cross-RAT spectrum/carrier aggregation as it would enable user data to be simultaneously transmitted over multiple Air interfaces; this can be also viewed as an extended LTE WiFi link aggregation (LWA). In addition, the proposed MAC allows for dynamic adaptation of different system parameters. This is necessary as different frame formats or channel configurations may need to be used for optimal performance, depending on the type of traffic and channel conditions. For instance, efficient operation of IoT devices requires narrowband transmission for achieving best performance. Inter-device and in-device coexistence also benefits from this flexibility.
- Ensuring a fair access to a shared medium is one of the main tasks of a MAC protocol. This

can be achieved either by implicit coordination or explicit coordination between nodes. The implicit coordination is usually based on different forms of sensing, duty cycle adaptation, or frame structure adaptation; whilst the explicit coordination requires exchange of messages between nodes for the reservation and identification of transmission opportunities. In order to enable efficient operation in a scenario where devices which support different RATs operate using shared resources, the SPEED-5G MAC is able to coordinate coexistence functions of different RATs. The proposed MAC design would be responsible, for example, for tuning sensing parameters, adapting duty cycle, or changing MAC frame formats. In case of a multi-RAT device, the proposed MAC would also facilitate the use of coexistence mechanisms provided by different RATs to enhance operation of another RAT; a good example could be here the use of Wifi radio interface for sending RTS/CTS frames to enable efficient LTE-U operation. In addition, devices which support multiple RATs may face different problems in case supported RATs operate using overlapping resources. In order to ensure coexistence in such a scenario, SPEED-5G MAC coordinates transmission of supported RATs to mitigate in-device interference.

- Implementation of Random Access Channel (RACH) differs depending on a RAT. To fully exploit this diversity, the SPEED-5G MAC manages different random access schemes to efficiently support different use cases such as eMBB on licensed and unlicensed spectrum or mIoT. This includes regulating the way users camp on to the network, changing the contention resolution strategy for various licensing regimes, and updating prioritisation of random access requests.
- Different RAT-specific power-saving mechanisms can be employed by multi-RAT devices. In order to enable efficient operation of such devices, the SPEED-5G MAC can coordinate and update configuration of power-saving mechanisms across different RATs.
- Different physical layers which operate using different waveforms (for example, Orthogonal Frequency Division Multiplexing (OFDM), Filter Bank Multicarrier (FBMC) as well as Non-Orthogonal Multiple Access (NOMA) techniques) can be used by the underlying RATs. In order to fully exploit this diversity, the SPEED-5G MAC is capable of tuning different parameters of underlying physical layers.
- Obtaining measurements is necessary for optimal allocation of resources in a wireless network. Inclusion of a dedicated monitoring interface between Higher MAC and Physical Layers allows direct communication between these layers resulting in higher flexibility, in terms of types of measurements, frequency of reporting and so on; and more efficient collection. The interface is intended to i) enable efficient and dynamic coordination of RATs, and ii) provide sensing and QoS measurements to cRRM, so as to feed the coarse-grained centralised resource management or centralised SON algorithms, with information need to coordinate small cell operations, over different time-scales.

The following high-level requirements have been captured from the selected use cases, driving the overall design of the MAC framework:

Table 1: L1 Requirements list

ID	**L1** (level 1)-**requirements**
R1	The MAC design shall enable single-RAT and multi-RAT operation across different technology specific and technology neutral bands (licensed, lightly-licensed or unlicensed).
R2	The MAC design shall support virtualisation and different RAN-split options.
R3	The MAC design shall support different random access schemes depending on RAT and their coordination.
R4	The MAC design shall support coexistence coordination, to enable fair access in technology-neutral bands
R5	The MAC design shall support provision of sensing & measurements management

	communication with the cRRM, coming from small cells and UEs.
R6	The MAC design shall support control of MAC functions by the cRRM through the higher protocol stack layers via well-defined interface(s)
R7	The MAC design shall support dynamic channel configuration, in technology-neutral bands
R8	The MAC design shall be able to support different traffic types and QoS requirements including IoT.
R9	The MAC design shall support backwards-compatibility with LTE-LAA and LTE-U standards.
R10	The MAC design shall enable aggregation of resources provided by different supported radio-access technologies.
R11	The MAC design shall enable traffic offload (user and control plane traffic).
R12	The MAC design shall provide sufficient flexibility to support future advanced air-interface designs

2.2 Performance metrics specific to the MAC-layer

In order to fully evaluate the proposed MAC designs and compare them with existing solutions, several performance metrics needs to be considered.

- **Throughput** – throughput reflects the portion of the channel capacity used for data transmission. User, cell, and radio link throughputs are among the most important performance indicators of QoS. At the MAC level, the objective is to maximize the throughput while minimizing the access delay. Different variants of the throughput metric can be defined. In this project we focus not only on the throughput metrics which provide information about the overall network performance (for example, *area network throughput* [bps/m2]) but also on the variants that reflect user experience, such as *average per node throughput* [bps], or the *5th percentile of per node throughput of a group of nodes* [bps]. An important variant of the throughput metric considered by the SPEED-5G is also the *saturation throughput* [bps] which provides information about the amount of user data that the system can successfully carry in saturation conditions (that is, when each node in a network always has packets to transmit).
- **Delay** – delay is defined as the average time spent by a packet in the MAC transmission queue, and is therefore a function of protocol and traffic characteristics. In general delay can be subdivided into *queuing delay* (that is, the time spent by a packet from the moment it is queued until it reaches the front of the transmission queue) and *medium access delay* (that is, the time spent by a packet in front of the transmission queue until it is successfully transmitted). Depending on the traffic model used, the delay metric may comprise either medium access delay (for example, in case of full buffer traffic model), or medium access delay and queuing delay. In order to better understand the impact of delay, *average delay* [ms] and standard deviation of delay (that is, *jitter* [ms]) shall be considered in our investigations. Similarly to throughput, we focus not only on the delay metrics which provide information about the overall network performance but also on the variants that reflect user experience (for example, *average per node delay* [ms], *5th percentile of per node average delay of a group of nodes* [ms]). An important variant of the delay metric considered by SPEED-5G is also the *saturation delay* [ms] which provides information about the delay experienced by user data in saturation conditions.
- **Fairness** – fairness metrics are used to determine whether users or applications are receiving a fair share of system resources. Scheduling of resources is considered fair if it does not exhibit preference to any single node when multiple nodes are trying to access resources. This results in fair sharing of the bandwidth/resources. In other words, a properly designed MAC protocol should ensure that all nodes are treated equally; that is, all nodes have an

equal chance of accessing the wireless medium. This is necessary to prevent the situation in which a subset of nodes obtains most of the channel's bandwidth and other resources while the remaining nodes starve. In order to account for different traffic classes, the *weighted fairness* can be considered in which the channel's bandwidth obtained by a node is proportional to its weight, which is based on QoS requirements of a specific traffic class. In order to measure fairness we propose to use *Jain's Index* and advanced variants, as proposed in [33].

- **Energy efficiency** – as most of end devices have limited battery power, MAC protocols often include different power-saving features designed to conserve battery power. This is particularly true for IoT devices with expected lifetime of 10 years on battery. In order to allow for a fair comparison between different MAC designs, proper metrics which measure the energy efficiency of MAC protocol are then required to assess the benefits of these techniques for the end-user. Average energy consumed per node per second and node lifetime selected by SPEED-5G as the main metrics of energy efficiency for IoT devices.

2.3 Summary

This chapter presented the protocol stack and MAC vision in SPEED-5G, in order to support the eDSA feature. Based on this high-level introduction, the next chapter presents the result of a project-wise work dedicated to the definition of the MAC framework which relies on a top-down approach. In particular, the next chapter delves into the proposed SPEED-5G MAC functional block diagram by defining the MAC functions which are required for the support of the eDSA mechanism and how MAC and RRM are working together by means of interfaces identification for control, data, and monitoring planes.

3 SPEED-5G MAC Framework

This chapter presents the overall functional description of the SPEED-5G MAC framework and details how the RRM and the MAC layers work together. The proposed functional design is based on a top-down approach which has been adopted in order to facilitate integration with, and enabling of, the concept of eDSA. For MAC-design purposes, additional functions have been identified and function decompositions (into more atomic functions), and new groupings of functions, have been performed. The most important aspects which have guided this design are

- Ability to address both an improvement of existing technologies based on carrier aggregation using bands under diverse license regimes, and native support for a new disruptive distributed TDD-MAC protocol where multi-connectivity and spectrum aggregation are built-in features.
- Native support for multi-RAT operation as 5G networks are expected to unify a broad set of RATs under the same network architecture.
- Decomposition of the MAC layer into a higher-MAC sublayer handling RAT cooperation and logical channel management and a lower-MAC sublayer supporting the RAT-specific functions.

3.1 Small Cell (SC)-side MAC function blocks and Interfaces

This section presents a detailed description of each function of the MAC protocol (cell-side) designed for small cells and depicted in Figure 2 below.

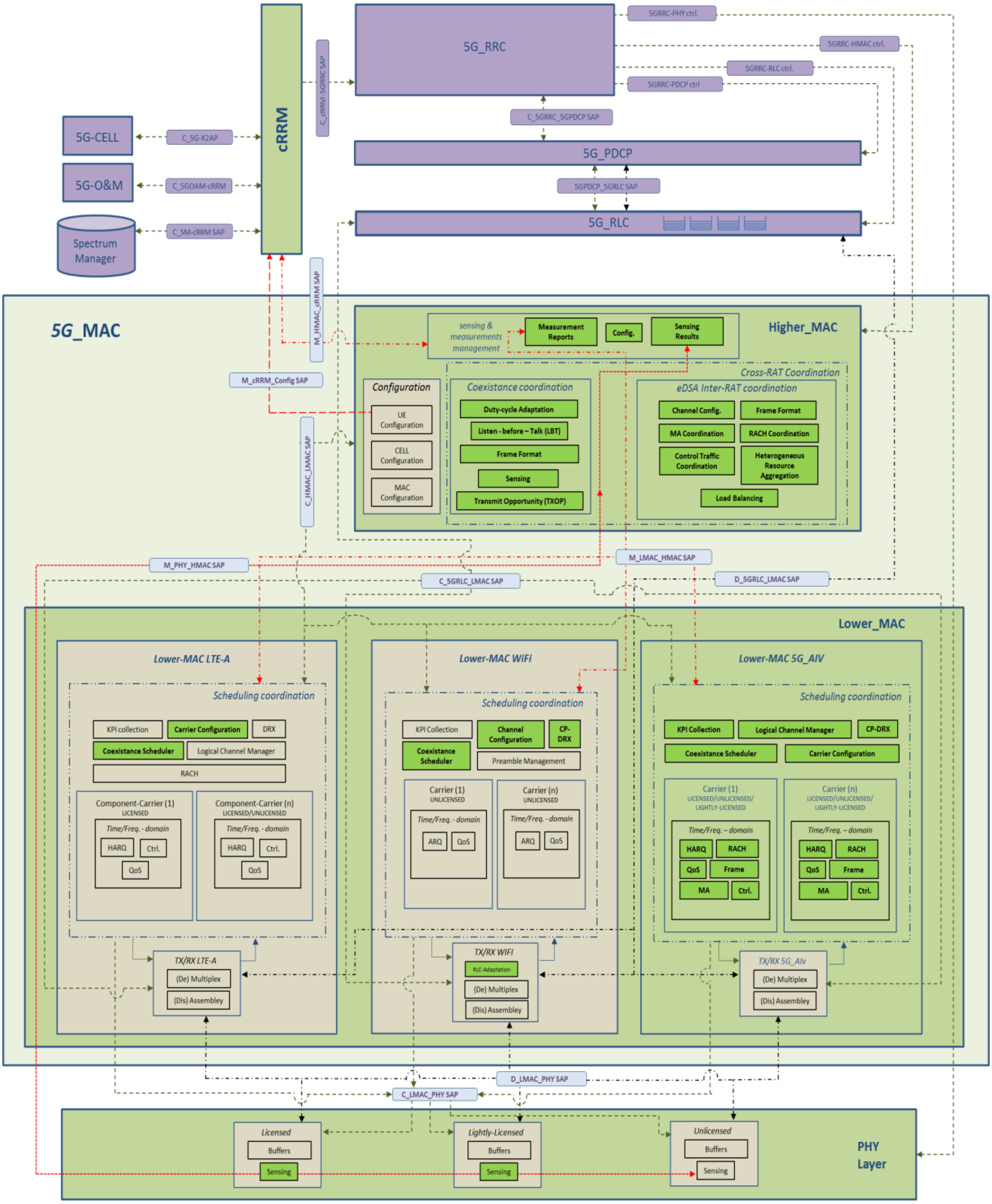

Figure 2: SPEED-5G SC-side MAC framework and functional blocks for eDSA support in small cells

External Interfaces i.e. between distinct layers or sub-layers :

Control/OAM	←- - - - -→
Monitoring (sensing)	←- - - - -→
Monitoring (MR)	←---------→
Data (u-plane)	←·-·-·-·→
Monitoring (HMAC config.)	←— — —→

Internal Interfaces i.e. between blocks within a given layer/sub-layer (i.e. no need to define SAPs) :

Interface (Config. > Measurement Reports & Config. > Sensing Results)	←——→
Interface (Scheduling Coordination > TX/RX)	←——→
Interface (TX/RX > Scheduling Coordination)	←——→

Colour-key:

- NEW Function-Groups in "Light-GREEN"
- **NEW Blocks/Functions in "dark-Green"**
- Legacy Blocks in "Grey"
- SAPs in "Light-blue"
- Blocks/interfaces "out-of-scope" of WP5, in VIOLET

The MAC protocol framework (designed for small cells) is connected to the cRRM entity of the architecture [2] via the 5G-RRC layer and is composed of 2 sublayers named higher-MAC and lower-MAC; the former copes with cell configuration and RAT coordination and coexistence in shared spectrum, and the latter with RAT-specific bearer management and data transmission and reception. In addition to the control plane and data plane, this block diagram interestingly includes a new kind of interface which carries all the sensing and KPI reporting data, for both RAT coordination and eDSA enablement at cRRM layer. An important aspect of this MAC design is that control and data planes are separated, having the higher MAC only dealing with control plane with no influence on the data path, which is handled at the lower-MAC level.

Note that the block diagram shows a 5G-RLC entity which is connected to the cRRM and to the lower-MAC, handling the active logical channels dedicated to all the RATs supported by the small cell. Whereas in existing systems, the traffic queues are treated as separated entities corresponding to specific RATs (LTE, Wifi, etc.), this novelty in SPEED-5G allows this block to expose to the cRRM the list of all active logical channels with the associated QoS requirements. It also provides the buffer statuses, needed by resource management algorithms to take decisions on how to make an optimal use of spectrum and RAT resources in the group of small cells it has to coordinate. 5G-RLC is also connected to the schedulers of the supported RATs in the lower-MAC, (configured by the higher MAC), applying the cRRM decisions on real time basis.

3.1.1 Higher-MAC

In order to enable eDSA operation, a set of high-level, RAT-independent functions for the SPEED-5G MAC layer have been defined. The main purpose of the proposed functions is to allow for efficient operation of single-RAT and multi-RAT devices across different technology specific and technology neutral bands (licensed, lightly-licensed, or unlicensed). The proposed functions enable efficient cross-RAT operation and improving inter-system coexistence. The following describes the proposed functions in more details.

3.1.1.1 Configuration functions

This higher-MAC entity contains the common configuration parameters related to the cell, the UE and the scheduler. The cell, UE, and scheduler are configured by the cRRM or the OAM through the **5GRRC_HMAC control** interface, depending on the situation and the scenario. For instance, the initial manual configuration can be done by the OAM while the auto-configuration is done by the cRRM algorithms based on the reported KPIs. The configuration data has to be easily accessible and maintain the integrity for scalability purposes.

- **Cell Configuration**: This module contains all the parameters related to the cell and used to configure the cell functionalities. The common parameters are, for instance, the supported RATs whereas the specific parameters per RAT refer, for example, to the frequencies supported by each RAT.

- **UE Configuration**: This module keeps the characteristics of the connected UEs and, depending on the MAC, the characteristic of previously connected UEs. This information is shared with the RRM in order to properly configure the MAC. This information is used by the MAC in order to schedule each UE.
- **MAC Configuration:** This function receives the cRRM decisions to be applied at MAC level, via the **5GRRM_HMAC control** interface. It distributes those long-term decisions, compared to the MAC real time constraints, related to carrier or resource aggregation to the “eDSA inter RAT coordination” entity like the logical channel (with QoS requirements) to offload on the different carriers along with the maximum bandwidth or transmit powers for instance. It supplies the “coexistence coordination” entity with parameters like the CCA threshold minimum and/or maximum values, a possible frame format as an initial state for further optimisations at MAC level. In the case of channel identification, it provides the identified spectrum band and possible preferred channels where the lower MAC has to focus on. As far as lower-MAC configuration is concerned, this function provides the RAT specific parameters like scheduler configurations or KPI computation methods.

3.1.1.2 Sensing and measurement management functions

This group of functions are responsible for collecting sensing results and link control KPIs (measurement reports) and forwarding them to the cRRM through the coordination interface **M_HMAC_cRRM SAP** and the **M_PHY_HMAC SAP**.

- **Measurement reports:** this module is in charge of handling the actual data. Sensing measurements are related to the different spectrum bands the small cell is able to operate and may corresponds to ad-hoc sensing procedures (channel selection for instance) or to run time procedures like clear channel assessments or CQI (CSI) reports. These sensing data are provided to the higher-MAC via **M_LMAC_HMAC SAP** from the TX/RX entities of RATs in lower-MAC and they pertain to link control performance indicators coming from the schedulers of the active RATs. They embrace BLER, latency, jitter of the active logical channels and CQI reports (UL and DL). These composite KPIs can be consumed locally within higher-MAC as inputs to algorithms for real time adaptation of traffic offloading decisions, for instance. They are also transmitted to cRRM via the **M_HMAC_cRRM SAP** for feeding centralised spectrum monitoring and resource allocation procedures. Given cRRM is dedicated to long term optimisation for resource allocation and interference management, forwarding to cRRM implies that optional data post-processing is required to reduce the bandwidth of the MAC/cRRM interface at the **M_HMAC_cRRM SAP**.
- **Sensing results**: This block contains the sensing data retrieved for the lightly and unlicensed spectrum band. This information is used by the scheduler to allocate radio resources on these bands but it is also sent to upper layers when required for cell coordination procedures. The sensing data, received via the **M_PHY_HMAC SAP,** are stored in the **Sensing results** database, and made available for other MAC functions and / or the cRRM entity via the **M_HMAC_cRRM SAP**.
- **Configuration**: This module provides the sensing and link control KPIs collection and reporting parameters. For measurement reporting, it specifies the format and rate of data measurements report from MAC to cRRM. For sensing, this function is able to provide the physical layer with parameters like detection method (energy detection, preamble detection), sensed bandwidth, sensing duration. It also receives sensing requests from cRRM in the case the latter wants to get updates on a given spectrum band in a background monitoring process. The configuration parameters and sensing requests are provided through the **M_HMAC_cRRM SAP** interface.

3.1.1.3 eDSA inter-RAT coordination functions

Together with "Coexistence coordination", this entity is the core set of functions which enable the eDSA at MAC level. It includes functions used to manage traffic steering, logical channel management for RAT and spectrum aggregation, multiple access, frame formatting, and broadcast. This group of functions are actually applying coarse-grained decisions taken at cRRM level, taking into consideration real-time conditions experienced at lower-MAC level in terms of capacity on active bearers. They are also able to modify the configuration of the lower-MAC like the frame format of the set of active channels which are steered on one or another bearer. Note that this eDSA Inter-RAT Coordination function entity has no direct interface and does not have real-time updates of the buffer status. The real-time adaptation on bearer configuration is enabled through communication with the lower-MAC, which is aware of the buffer status thanks to its connection with the 5G-RLC entity. Communication between the lower-MAC and 5G-RLC is via the **C_5GRLC_LMAC SAP** and **D_5GRLC_LMAC SAP**, respectively for control and data planes.

- **Channel configuration**: This function provides the optimal channel configuration for the different combination of carrier and air interfaces. It selects the bandwidth configuration in unlicensed bands, defining the channelization bandwidth (20 MHz, 40 MHz), the extension or secondary channel above or below the primary channel and the channel bonding for WiFi 11ac carriers, defining band guard intervals, and other channel-related functions like Dynamic Frequency Selection or Transmit Power Control (TPC), where DFS is required. This function also acts over licensed and lightly licensed spectrum defining sub-channels for IoT services which use lower channelization bandwidths, collaborating with the cRRM in the cross-cell coordination in order to reduce interference by means of defining different spectrum chunks for low bandwidth IoT services across different small cells, coordinating the spectrum allocation for these services, when the IoT slice is active.

- **Load balancing**: This function receives load balancing guidelines from cRRM through the 5GRRC_HMAC_Ctrl interface , which gives the balancing scheme which has to be applied on a long time scale (say hundreds of ms). These guidelines relates for instance on which class of traffic should be steered on which kind of spectrum band, with no further details about channel configuration, identifiers of active logical channels which have to be mapped on spectrum resources. This function would allow a SC to convey time-critical control information for RATs operating in an overloaded unlicensed band using RATs operating in a licensed band, thus ensuring proper reception. This function maintains a table which stores what are the active logical channels and their associated QoS requirements. It needs to be highlighted here that this function does not know the actual buffer status at RLC level.

- **Heterogeneous resource aggregation**: 5G nodes are envisaged to support multiple RATs through the SDR technology, being able to host more air interfaces (AI) than physical RF interfaces, reconfiguring in real time the underlying AI over each RF interface, for implementing different transmission schemes according to the services delivered by the small cell. The Hybrid Spectrum Aggregation generalizes the carrier aggregation concept, typically applied to licensed technologies like LTE in order to extend this concept towards legacy RATs. More specifically, the 5G-AIV can support new aggregation schemes thanks to the distributed nature of the MAC design that can dynamically coordinate the aggregation scheme according to the instantaneous cell loading and interference levels. This function is necessary to fully exploit the availability of resources from different RATs, as it manages distribution of load and the aggregation scheme across different RATs.

- **Control Traffic**: This function is responsible for steering and coordinating transmission of control traffic. Its main aim is to facilitate transmission of control traffic of one RAT over control channels of another RAT (this includes broadcast traffic and dedicated control traffic). The function makes its decisions based on information received from cRRM and from lower-MAC entities. In case of a single-RAT device, the function aims at improving utilization of resources allocated for control channels by lower-MAC entities.

- **RACH**: This function is responsible for coordination and adaptation of random access schemes employed by different underlying RATs. The function aims at regulating the way multi-RAT devices access the network, for example, which RAT to use for network access in different situations. It adapts contention-resolution strategies and regulates the amount of resources allocated for random access in the underlying RATs (for example, depending on a licensing regime of a channel, or a type of traffic).
- **Frame format**: Given the QoS requirements of the active logical channels and how they are mapped on the different carriers, the different frame formats on the active bearers are tuned by this function in a suitable way, related to the expected service KPIs such as BLER and latency. For instance, the ratio between uplink and downlink resource or scheduled and contention based access resources (such as time slots) can be tuned to meet latency demanding or best-effort services. As well, this function can take the decision of modifying the transmission parameters and PHY numerology in general, like TTI and slot duration or multicarrier filter configuration, to accommodate for instance logical channels having a strong latency requirements or low-end computational capabilities.
- **Multiple Access (MA)**: This function covers the configuration and adaptation of lower MAC components, taking advantage of orthogonal and non-orthogonal multiple access schemes an. For example, this function can control FBMC parameters to govern the trade-off between filtering depth and adjacent channel leakage ratio and make the latter smaller when the spectrum resource is densely crowded. As well, it can modify the numerology of the PHY, increasing or reducing the number of subcarriers in the guard band, which can allow for a trade-off between spectral efficiency and multiple access interference mitigation complexity. For lower MAC supporting NOMA, this function provides default parameters to manage the different actives UEs, given the UE localisation, the QoS requirements of the active logical channels.

3.1.1.4 Coexistence coordination functions

This group of functions is responsible for ensuring proper coordination of transmissions on different RATs when the medium has to be shared (in-device interference management) and also ensure an efficient exploitation of technology-neutral frequency bands (inter-device interference management). This covers features like duty-cycled operation, listen-before-talk, decision-making on sensing events, or adaptation of the frame structure to manage the interference with other neighbouring systems. As mentioned earlier, nodes which support multiple RATs may face different problems in the case in which supported RATs operate using overlapping resources. Communication between the cRRM and 5G-RRC is done through the **5GRRC_HMAC control** interface and communication with the lower-MAC is via the **C_5GRLC_LMAC SAP** for control purpose.

- **Duty-cycle adaptation**: This function is responsible for managing coexistence in a shared spectrum, adopting a time-domain spectrum utilization pattern approach, reducing the probability of collision with neighbouring systems by respecting an ON-OFF operation of the transmitter. Referring to state-of-the-art technologies, this function is included in the CSAT operation of LTE-U [29] where LTE-U transmissions are gated according to observed activity on the 5 GHz band. It also covers the periodic listen-before-talk specified by ETSI [5] where the clear channel assessment (CCA) period and measurement duration, as well as the inactive period after occupying the channel are parameters that can be tuned depending on the QoS requirements and/or how frequency resource is loaded. This function deals with the implementation of such a technique as well as with the adaptation of parameters.

- **Listen-before-talk:** This function refers to coexistence methods based on the detection of on-going traffic on a shared frequency resource prior to the data transmission. For instance, it covers the CCA function used for the access in Wifi or in LBT procedure specified by ETSI for accessing the 5 GHz band. This function is responsible for managing the sensing duration, the detection methods (energy detection, preamble detection), configuring the physical layer or lower-MAC accordingly, and processing the sensing results comparing them with tunable detection thresholds.
- **Frame format:** This function, similarly to the frame format coordination described in the context of eDSA Inter-RAT coordination, is responsible for adapting the MAC frame structure of the different active bearers. However, in contrast to its counterpart, this function reacts to the changes in the channel quality, rather than to the changes in the traffic conditions and aims at enabling better coexistence. A good example of improving coexistence by exploiting frame format adaptation is the LTE scheme based on the use of Almost Blank Sub-frames (ABS). Similarly to its counterpart, the function can change the ratio between uplink and downlink resource (or scheduled and contention based access resources), or modify different transmission parameters such as TTI/slot duration and multicarrier filter configuration.
- **Transmit opportunity**: This function has the role of managing the contention processes applied on the different RATs, when relevant. It enhances for instance the CSMA/CA process for WIFI or FBMC transmission on shared spectrum. This function also deals with the number of possible attempts (or retransmissions) and the back-off policy. It works in closed-loop with the **listen-before-talk** function which triggers the contention-based medium access algorithms; when a transmit opportunity is valid, this function triggers the lower-MAC to proceed with the data transmission. The function could also facilitate the use of coexistence mechanisms provided in one RAT to enhance operation of another RAT; for example, RTS/CTS frames could be sent over a Wifi radio interface to improve LTE-U like operation.
- **Sensing**: Implementation of sensing and its capabilities (that is, which spectrum bands which can be sensed) differs depending on a physical layer. In order to fully exploit this capability in a device which supports multiple physical layers (or multiple sensing techniques), a function is needed which enables coordination and effective use of different sensing mechanisms as well as sequential sensing of different bands. This block provides such functionality and thus enables the SPEED-5G MAC to efficiently manage sensing. The parameters which can be configured by this block include sensing duration, minimum signal detection level, and sampling rate. Lower-MAC

The lower-MAC is the workhorse of the Speed-5G MAC Design. It comprises of the different schedulers and Rx/Tx functional blocks, each tied to an AIV. It consists of two main blocks: the **Scheduling Coordination** and the **TX/RX**. The LTE-A and WiFi Scheduling Coordination blocks are legacy, which are effectively integrated into the MAC framework with little modification. Those 5G AIV Scheduling Coordination and TX/RX functions blocks are beyond the state-of-the-art are described below.

3.1.1.5 Lower-MAC 5G-AIV interfaces

The Lower MAC interfaces with 5G-RLC through the **C_5GRLC_LMAC SAP** and **D_5GRLC_LMAC SAP**, Higher MAC through **C_HMAC_LMAC SAP** and PHY, through **C_LMAC_PHY SAP**.

The interface **C_LMAC_PHY SAP** is used by the different schedulers in the Lower-MAC in communicating with the PHY layer, by sending PHY configurations that can be deployed on the fly, according to the specific needs of the active slices and its related QoS requirements, like the real-time framing configuration, and numerology in adapting the transmission and the reception to the needs of the underlying network services and also in receiving some transmissions from certain devices with very low-end capabilities. This is the single point of contact in configuring the PHY layer and this is a pure real-time interface that is always active after the cell activation.

The interface **C_HMAC_LMAC SAP** is used for the communication between Higher-MAC and scheduler(s) in the lower-MAC, and it is mainly used for the control and configuration of the scheduler (for example, CQIs, rank indicator, interference information (SINR) per RB, per user, wideband SINR, power etc.), in order to provide the scheduler the needed information in taking link-adaptation decisions and other transmission decisions, as well as other static and dynamic control information for the scheduler such as thresholds, eDSA real-time-related configurations derived from eDSA functions and the result of their algorithms, or measurement reports decoded in higher layers, like UE measurement reports sent through RRC messages to be applied for Modulation and Coding Scheme and Index Transport Block Size (MCS_ITBS) calculations.

The interface **C_5GRLC_LMAC SAP** is used for communications between the scheduler(s) in the lower-MAC and the 5G-RLC entity, sending Transmission Opportunities (TxOps) to the different 5G-RLC logical channels, in order to get 5G-RLC PDUs of the size defined at the TxOp from the different logical channels. It also transports the buffer status information of each 5G-RLC entity related to every logical channel, allowing the scheduler QoS function to calculate based on the input variables (number of bytes in DL, number of bytes in UL, bitrate, jitter latency, etc.), the number of bytes to request 5G-RLC layer to transmit, in meeting the QoS requirements of every service.

The data plane is fully separated from the scheduler in order to reduce latency, as the user traffic is directly sent to the 5G-RLC without passing through the Scheduling Coordination functional block. The interface for this is the **D_5GRLC_LMAC SAP.**

The **internal interface** (in solid green) allows communication between the scheduler with the 5G-AIV Tx/Rx entity (inside lower-MAC) and it is mainly used for sending control information to the 5G-AIV Tx/Rx entity for multiplexing or de-multiplexing information, for resource allocation through scheduling requests or buffer status reports, for UE content resolution, for timing advance measurements, for CP-DRX information, for D_CTRL information, for power headroom, for carrier activation, for HARQ processing, for real-time framing configuration and PHY realization and for Transport Block assignment to the different underlying PHYs and timing information based in the subframe number.

The **internal interface** (in solid blue) is used for forwarding measurement information from the 5G TX/RX entity to the scheduler, like CQIs, rank indicator, interference information (SINR) per RB, per user, wideband SINR, power, in order to provide the scheduler the needed information for taking link adaptation decisions and other transmission decisions.

The control and configuration of the 5G-AIV TX/RX entity is achieved through the **internal** interface (in solid green). This interface supports communication between the 5G-AIV TX/RX entity and the scheduler(s) and provides control and configuration to the TX/RX functional block.

The data plane management is achieved through the **D_5GRLC_LMAC SAP** and the **D_LMAC_PHY SAP**. These SAPs manage the data plane transmission in both DL and UL directions.

The **D_5GRLC_LMAC SAP** is used for receiving (DL) or sending (UL) 5G-RLC PDUs to/from the 5G-RLC buffers. This allows sending or receiving specific data to or from the different active streams or logical channels if there is information for them.

The **D_LMAC_PHY SAP** is used for receiving (DL) or sending (UL) Transport Blocks to/from the different PHY layers of the different RF interfaces active in the SPEED-5G cell and the lower-MAC. This allows sending or receiving specific data to or from the different active RF interfaces of the cell configured with this RAT or AIV.

The control plane management is achieved through the **C_5GRLC_LMAC SAP** and the **C_LMAC_PHY SAP**. These SAPs manage the control plane transmission in both DL and UL directions.

The **C_5GRLC_LMAC SAP** is used for transmitting the description of how the 5G-RLC SDUs are multiplexed together with control elements in the transport blocks. This interface is also used to configure and update the required scheduling parameters of the cell, the UEs parameters, the supported schedulers and QoS characteristics. Furthermore, the configuration associated to UEs or QoS may be released by RRM or OAM when required. Other configuration parameters as transmission power or transmission bandwidth are also provided

The **C_LMAC_PHY SAP** is used to transmit and receive control messages that control for instance the HARQ procedures at the PHY, and also responsible for sending the configuration data to the PHY, including modulation and coding schemes applied on the physical channels, transmit power, channel configuration, as well as the eDSA-related configuration requests related to PHY, like NOMA control parameters for instance.

The monitoring plane management is collectively managed through the **M_PHY_HMAC SAP** and **M_LMAC_HMAC SAP**.

The **M_PHY_HMAC SAP** interface is used by higher-MAC to PHY for sending sensing requests and by the PHY to send back sensing results. The sensing information is related with coexistence, coming from the PHY layer to the sensing & measurement management, located at the Higher MAC sublayer.

The **M_LMAC_HMAC SAP** interface is used to convey Performance Counters and KPIs generated at the scheduler and for sending measurements.

3.1.1.6 5G-AIV Scheduling Coordination function blocks

The following functions are integrated into the **Scheduling Coordination** block:

- **KPI Collection**: This function provides the different performance counters and KPIs generated or calculated by the scheduler to higher layers. These counters can include information about used RBs per TTI in DL or in UL, number of active users, users scheduled per TTI, interference level, etc., and this information is collected by the KPI collection block and then forwarded to the Sensing and Measurement Management functional block in the higher MAC through **S_LMAC_HMAC SAP**. This function also builds some pre-processing of some Performance Counters like means or weighted means using active periods for getting more meaningful information.
- **Carrier Configuration**: This function applies the optimal channel configuration for the 5G-AIV according to the guidelines provided by the *Scheduler Configuration* function located in the Higher MAC. It configures the scheduler in real time for using specific numerologies (for example, channel bandwidth and intra-channel sub-bands).
- **CP-DRX**: This function provides the dynamic allocation of the Control Plane region for both the common control information for the cell control and the UE-specific control information, which is highly related to the underlying service in order to optimize the overall resources delivered to signalling and control information for reducing the overall overhead of the signalling and control of the cell, while minimizing the energy consumption at the UE side because of the optimal transmission of the control region and the reduction of the amount of control information to be decoded in periods where the UE or the cell is transmitting. It enhances the DRX operation, generalizing this concept to the overall control region of the cell, providing service-aware control strategies. The behaviour of CP-DRX can be dynamically adapted by the Control Traffic Coordination function located in the higher-MAC.
- **Coexistence Scheduler**: This function applies the coexistence decisions taken by the Coexistence Coordination function of the Higher MAC by adapting different coexistence mechanisms such as LBT, supported by the lower-MAC. This way the

higher-MAC can be specialized in coordination of coexistence mechanisms located in different Lower-MACs leaving the execution of these decisions (such as changing the duty-cycle adaptation parameters or changing the contention window size) to lower-MAC entities.

- **Ctrl:** This function is responsible for applying changes in the scheduler configurations and policies, provided by higher layers. It is the single point of contact for scheduling functions configurations and maintains information about all the active configurations for every carrier.
- **Logical channel manager**: This function maintains different logical channels (or streams) taking into consideration QoS requirements defined by means of stream QCI classification. The function maps logical channels (or streams) to possible transmission configurations, considering potential QoS which can be provided by these configurations (the set of possible transmission configurations may be affected by Higher MAC). This mapping is then taken into account during the resource allocation to prioritise the transmission of one precise stream over one specific 5G AIV configuration and frequency band, applying in real-time the cRRM decisions for traffic steering and service allocation, like in the case of IoT or URC, where there are specific requirements to be met.
- **Time and frequency domain scheduler**: Fast and adaptive scheduling in both time and frequency domains reduces jitter, latency and improves the spectral utilization enhancing the available cell bandwidth and maximum peak rate. The channel's decorrelation in frequency and time provides the possibility to exploit the varying conditions in both domains, by means of decoupling both domains, applying specific and differentiated algorithms over these two domains. The time-domain scheduler implements algorithms and mechanisms to determine which users are served in a given transmission time interval, whilst the frequency-domain scheduler assigns spectral resources to these users (taking into consideration re-transmissions and QoS related information). The frequency scheduler can take advantage of different information (if available) to optimize the resource allocation (such as channel quality measurements, HARQ reports, cRRM information for inter-cell coordination). It is worth noting that the scheduler can also allocate resources for random access allowing multiple users to content for resources. This block contains several functions that manage transmission of control information (by applying the CP-DRX decisions), manage retransmissions (by reserving resources for retransmissions), manage configuration of random access (by affecting contention resolution strategies), and manage the QoS aware algorithms.
- **HARQ**: This function provides the Hybrid ARQ buffers management, managing the Layer-2 re-transmissions in both uplink and downlink. HARQ provides low-level and fast high-rate forward error-correcting coding and ARQ error-control. The function reserves resources for re-transmissions, and indicates whether to use the same or different resources. As some devices are envisaged to not support HARQ for energy consumption optimization purposes (e.g. low-end IoT devices), the function can be deactivated.
- **RACH**: This function is primarily responsible for reservation of resources for Random Access. It indicates the time and the spectral resources that could be used for such purpose, handles contention resolution and priorities access requests. The function receives and applies decisions from the RACH Coordination function of the Higher MAC which allows for dynamic adaptation of random access strategies depending on, for example, traffic type, licensing regime or channel load. Note that 5G-AVI also supports resource-reservation for the DL as well as for UL initial access.
- **QoS**: This function provides the QoS-aware operation for the scheduler prioritizing

users in the time (and possible frequency) domain according to their QoS requirements in terms of latency and bandwidth. This function executes a global optimization function, which has as inputs the QCI of the different streams or logical channels of each user, the type of devices connected to the cell, the delivered network services, the maximum achievable bitrate for each user, the number of users and the available carriers deployed into a cell. This function also selects and prioritizes configuration for different RF interfaces having as an input the wideband SNR of the channel (or channels, in case of unlicensed spectrum) and user's particular CQIs in order to obtain the maximum achievable performance of the cell.

- **Multiple Access (MA)**: This function provides the control over the multiple access strategies of all users in the cell during their session times, implementing a non-orthogonal multiple access (NOMA) strategy when it is required; for example, orthogonal multiple access could be used with low load whilst non-orthogonal multiple access with high load. In general, the use of NOMA can reduce latency and improve spectral efficiency by serving all users at the same time and enabling access to all the subcarrier channels. Because of that, the MA function could potentially allow for more efficient handling of users with poor channel conditions (allowing them to share resources with users experiencing good channel conditions), thus significantly improving the overall spectral efficiency of the cell. Additionally, the MA function analyses the power headroom information sent by the UEs and sends SIC configuration to UEs, setting the classification for the cooperative NOMA where some UEs relay transmission to cell edge users. In this context, the MA function configures the user pairing to keep the cell computational resources and overhead under control (SPEED-5G design assumes that only a pair of users can be linked for cooperating). The application of NOMA is a key technology that empowers the eDSA concept, as it is highly beneficial to shared licensed frequency bands with cognitive radio systems, because more secondary users can be admitted by using NOMA [49], enhancing the advanced support of licensed shared access in SPEED-5G systems.
- **Frame**: This function provides the frame configuration to the PHY and also to the time-frequency domain scheduler, as it defines the time transmission interval, the system slots and timings, the framing aggregation in terms of sub-frames (or slots) and defines the basic time-frequency grid for being used in the scheduler. This function receives frame configuration decisions from the Frame Format function located in the Higher MAC in order to execute in real time the above mentioned framing configuration decisions.

3.1.1.7 5G-AIV TX/RX function blocks

The functions that are integrated into the **TX/RX block** are the following:

- **(De-)Multiplexer:** For the downlink path, this function multiplexes 5G-RLC SDUs and other information like Broadcast Information SDUs or MAC control elements into Transport Blocks to the different active RF interfaces of the cell configured with this RAT or AIV getting the information from the different sources (scheduler, 5G-RLC). For the uplink path, this function 1) de-multiplexes Transport Blocks into 5G-RLC SDUs and other information (e.g. UE measurement reports such as CQIs, RIs or MAC control elements) from different active RF interfaces of the cell, 2) sends the de-multiplexed information to the proper SAPs.
- **(Dis-)Assembler:** For the downlink path, this function assembles the downlink information into Transport blocks coming from the Multiplexer function according to the MAC-PHY API message formats and timing constraints for sending the information to the PHY layer. For the uplink path, this function disassembles PHY messages for splitting the incoming information into readable information to feed

the De-Multiplexer function.

3.1.2 Lower-MAC WiFi

This section briefly discusses the WiFi lower-MAC, to clarify the use of the terms “Time-frequency domain scheduler” and “CP-DRX” in the context of WiFi lower-MAC.

Depending on the configuration and implemented features, channel access in WiFi can be classified as contention-based (random) and contention-free (scheduled). In case of contention-based access all UEs and BSs contend on equal rights for channel access. In case of contention-free access, a BS coordinates transmission by assigning resources for transmission to each UE. The use of the term “Time-frequency domain scheduler” in the context of WiFi is necessary to cover both these options as well as the future support of OFDMA and Uplink MU-MIMO (currently standardized by IEEE 802.11 WG [41]). In case the contention-free access is not supported, the role of the scheduler in the SPEED-5G design is simply limited to continuous allocation of resources for contention-based access.

Regarding the CP-DRX, its role in the WiFi lower-MAC is limited to adaptation of transmission parameters of management and control frames. A good example of such a frame is the beacon frame which carries different common control information and is transmitted periodically by Access Points. In case of beacons, CP-DRX regulates the amount of information which is sent and affects the frequency with which beacons are transmitted. Such a mechanism is necessary, e.g., to allow support of a scenario in which some of information usually carried by beacons is transmitted over other air interface (such as LTE) for better reliability.

3.1.3 MAC control plane interface

The new control-plane interfaces (logical channels between higher-MAC and lower-MAC entities, as well as between MAC and 5G-RRC, 5G-RLC and PHY) are summarized in Table 2.

Table 2: New internal C-plane SAPs and interfaces

Interface	SAP(s)	Direction	Blocks involved
CI_1	C_HMAC_LMAC SAP	HMAC <> LMAC	higher-MAC and low-MAC [scheduling coordination]
CI_2	C_5GRLC_LMAC SAP	5GRLC <> TX/RX	5G-RLC and low-MAC [TX/RX]
CI_3	C_LMAC_PHY SAP	LMAC > PHY	PHY and low-MAC [Scheduler blocks]

3.1.4 MAC user plane interface

The new user plane interfaces (logical channels between higher-MAC and lower-MAC entities) are summarized in Table 3.

Table 3: New internal U-plane SAPs and interfaces

Interface	SAP(s)	Direction	Blocks involved
DI_1	D_5GRLC_LMAC SAP	5G-RLC <> TX/RX	5GRLC and low-MAC [TX/RX]
DI_2	D_LMAC_PHY SAP	PHY <> TX/RX	PHY and low-MAC [TX/RX blocks]

3.1.5 MAC monitoring plane

In order to enable eDSA, the SPEED-5G MAC framework has been designed to incorporate a novel plane besides control and data planes, for control, management, reporting and collection of the sensing and radio link control KPIs, named ***monitoring*** plane. Because it involves functions spanning on the different RATs and because it relates to heterogeneous resource management, the monitoring plane has been decoupled from control plane. The monitoring plane manages sensing and KPI collection and reporting, to higher layers.

It is represented via red arrows in Figure 2. The monitoring plane is interfaced with cRRM which is able to get raw or pre-processed sensing and KPI data sets from the different small cell it coordinates in order to feed the RRM algorithms and issue optimised resource utilisation decisions. The monitoring plane at MAC layer is composed of two main components coming either from PHY or lower MAC components, which report two kinds of data sets, explained below.

Monitoring plane towards the PHY is about configuration, requests and reporting of RF sensing data coming from the different PHY components, on either licensed, lightly-licensed or unlicensed spectrum. The collected data set (see) are related to spectrum scanning or measurements on specific RF channels. They are reported from PHY to the “sensing results” block at the higher-MAC level where they are stored and made available either for cRRM via the communication modes detailed in the next subsection or for higher MAC blocks like “load balancing” or “heterogeneous resource aggregation” for instance.

As far a link-control KPIs are concerned, they are provided by the “KPI collection” of the lower MAC components (see Table 5 for measurements items) through the M_LMAC_HMAC SAP. Note that this “KPI collection” block may also be fed by inputs coming from the TX/RX entity, where measurement reported by UEs or MAC level measurements are extracted and forwarded to the former block.

Table 4: New monitoring (sensing) SAPs and interfaces

Interface	SAP(s)	Direction	Blocks involved
MI_1	M_HMAC_cRRM SAP	HMAC <> cRRM	cRRM and HMAC [sensing & measurements management]
MI_2	M_LMAC_HMAC SAP	LMAC <> HMAC	LMAC [KPI collection] and HMAC [sensing & measurements management]
MI_3	M_PHY_HMAC SAP	PHY <> HMAC	PHY [sensing] and HMAC [sensing & measurements management]
MI_4	M_cRRM_Config SAP	HMAC > cRRM	cRRM and HMAC [Configuration]

3.1.5.1 Communication modes

The communication between cRRM and MAC layer is done under 3 types of traffic patterns, using the **M_HMAC_cRRM SAP**.

- Periodic report: cRRM configures the higher MAC to send sensing and KPIs reports on a periodic basis, which can be modified at run time. The value of the reporting period highly depends on the backhaul capabilities but is much longer than the scheduler granularity, which is 1 ms for LTE-like systems. The configuration is done through the “Configuration” block of the “Sensing and measurement management” entity in the Higher-MAC.
- Event-based report: depending on the criticality of the sensed data or KPI, the cRRM can

configure the higher MAC to send report when a specified event occurs. It can be for instance the sideband SINR of a shared band which goes below a certain threshold or when the experienced latency of a given logical channel is higher than the expected limit.

- On-demand report: in the case cRRM needs an update on a particular resource (spectrum band, history of logical channels management of a certain class of service on a given frequency band), it will send an on-demand request to the higher-MAC for this report. This request can be forwarded to PHY and/or to lower-MAC entities using the M_PHY_HMAC SAP and M_LMAC_HMAC SAP respectively.

The configuration can be done using a request-confirm transaction pattern (shown in Figure 3), using primitives[2] such as:

- MAC_MEAS _CONFIG_REQ: defining the type of communication mode (periodic, on-demand, event based) and the measurements required by the cRRM and the possible measurement methods (such as clear channel assessment modes and threshold levels). Upon reception of such a request, Higher-MAC forwards the request to lower-MAC entities (schedulers) using the same communication.
- MAC_MEAS_CONFIG_CNF: sent by Higher-MAC to cRRM as a response to the configuration request.

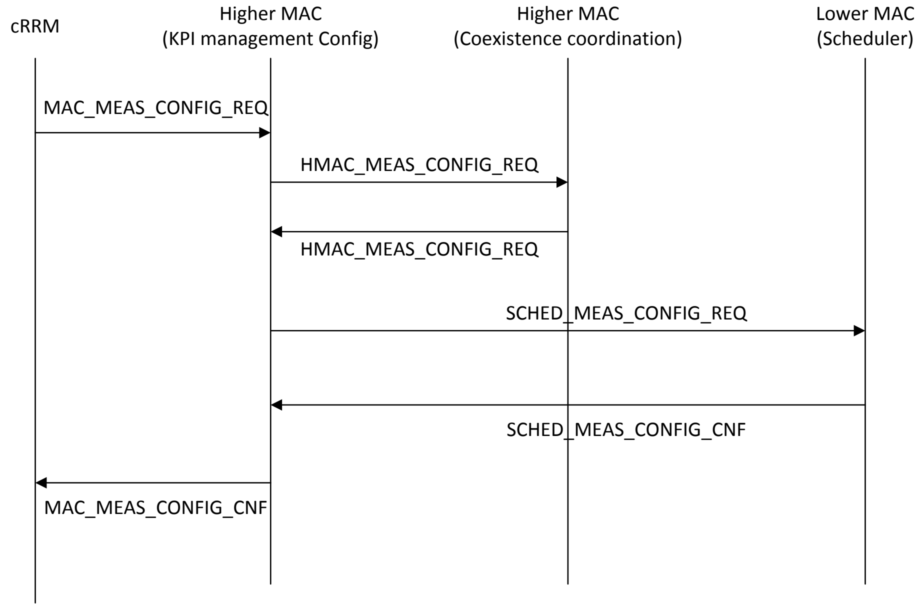

Figure 3: Measurement/sensing configuration procedure

On-demand sensing reports are triggered by a primitive initiated by cRRM, requesting the type of measurements, which can be possibly distributed on lower-MAC or PHY components using the same request-confirm pattern, like follows.

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[2] The names of primitives given in this section are indicative and will be refined and locked down later.

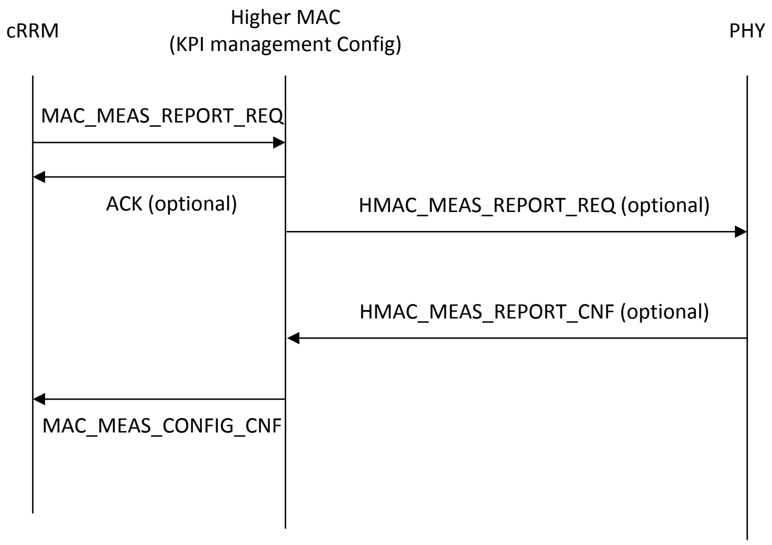

Figure 4: On-demand measurement/sensing reporting

As far as sensing and KPI reports transmission is concerned, periodic and event-based reports can be sent from Higher MAC KPI management block to RRM using a straightforward "indicate" primitive, MAC_MEAS_DATA_INDICATE, containing the description of the data structure and the data themselves.

3.1.5.2 Sensing reports and KPI measurements

This section gives a first list of sensing measurements and link-control metrics that are considered within SPEED-5G as relevant reports items. This initial listing shown in Table 5 will be complemented and consolidated further after a joint work with WP4.

Table 5: Measurement report types

Item	Comment	Originator
Wideband SNR	Per identified band / channel	From PHY
Energy level (from ED)	Per identified band / channel	From PHY
SINR per resource block	Per active logical channels	From schedulers
BLER/FER	Per active logical channel	From schedulers
CQI	Per active logical channel	From schedulers
Latency	Per active logical channel	From schedulers
RSRQ/RSRP/RSSI	Per active logical channel	From schedulers
CIR (channel impulse response)	Per physical channel	From TX/RX

3.2 UE-side MAC Function blocks and Interfaces

This section presents a detailed description of each function of the MAC protocol designed for UE and depicted in *Figure 5*.

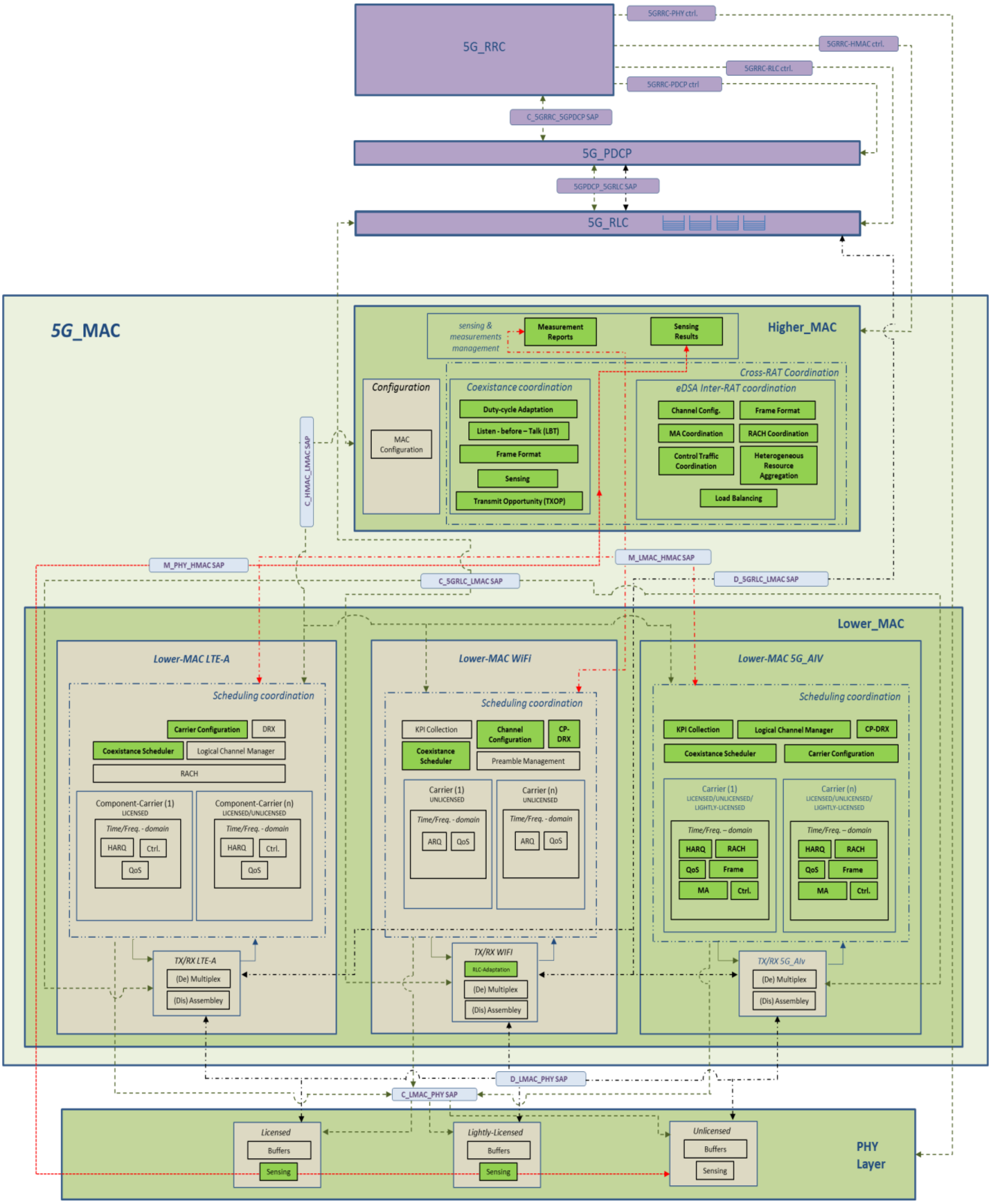

Figure 5: SPEED-5G UE-side MAC functional block diagram for eDSA support in UEs

A scalable and flexible MAC, which is able to coordinate, optimized and efficient usage of radio resources using a heterogeneous set of RATs has been introduced above for the SC. Going forward, there is also the need to look into a scalable, flexible and a unified MAC framework for the UE, which is able to support all the services and use cases described in D3.2 [2] and most importantly, the functionalities identified in the SC MAC in the sub-section above.

Figure 5 shows the identified UE MAC functional blocks and the interfaces. Compared to the SC MAC functional blocks in Figure 2, the UE MAC hosts only a limited set of functionalities.

Following the multi-RAT approach of the SC, each supported RAT or AIV in the UE has its own MAC scheduler. If a scheduler for a specific RAT is not implemented or de-activated, then the UE does not support such a RAT within the period that the corresponding scheduler is de-activated. This introduces configurability in the UE design and can scale well, based on its service requirement and also the spectrum on which it can best operate. The SC can choose to switch some of the MAC schedulers of the UE on and off, depending on the overall network load condition.

As it is in the case of the SC MAC, the UE MAC is also divided into two parts: Higher MAC and the Lower MAC. SC is expected to configure the higher MAC and the different MAC schedulers in the lower MAC. Depending on the capabilities of the UE and also the availability of supported spectrum bands, under the control of the SC, the UE can operate autonomously for a configurable period of time.

The sub-sections below describe the UE MAC functional blocks and interfaces, focusing on the subtle differences from the SC-side MAC.

3.2.1 Higher-MAC

The Higher-MAC in the UE serves a similar purpose, as its peer in the SC MAC. It interfaces with the 5G-RRC through **5GRRC_HMAC_Ctrl**, the Lower MAC through the **C_HMAC_LMAC SAP** and the PHY layer through **S_PHY_HMAC SAP**. Depending on the capabilities of the UEs or devices, not all functional blocks will be implemented. The SC is expected to configure the higher MAC, and the higher MAC will in turn coordinate the real-time operation of the different RAT specific schedulers in the lower MAC.

3.2.1.1 Configuration functions

- **MAC Configuration:**

  In the UE, and also for the SC, the lower MAC schedulers require a tight synchronisation with the underlying PHY. Lower MAC schedulers support real-time functionalities such as HARQ procedures, Random Access (RA) procedures and etc. which, if not properly synchronised with the SC can lead to packet drops, radio link failure, connection drops and etc. To facilitate this synchronisation, the Higher MAC configures the UE's lower MAC on how it should operate. These semi-static configurations will be stored in the "MAC Configuration" sub block and they come from 5G-RRC through **5GRRC_HMAC_Ctrl** interface.

  Also as described at the SC, the higher MAC has harmonised the coexistence and real-time coordination functionalities that otherwise would have been performed by the lower-MAC schedulers in standalone mode. This facilitates the flexibility in adopting and integrating new AIV's into the framework. Coexistence functionalities like LBT, duty cycle coordination and periodic and aperiodic reporting of sensing results are all controlled by the SC. These required configurations will be sent to the Higher-MAC layer through the **5GRRC_HMAC_Ctrl** interface.

  All these configurations are locally stored in this functional block.

3.2.1.2 Coexistence Coordination functions

This functional block has been well introduced at the SC above. In the UE, the functional description at the SC also applies. It coordinates the coexistence of the different MAC schedulers in the technology-neutral spectrum bands (unlicensed, lightly-licensed) and even some licensed spectrum. LBT, CSAT, sensing are some of the well-known coexistence techniques which are adopted in this functional block.

- **Listen-before-talk:**

  Carrier Aggregation (CA) has become one of the pillars on which cellular operators boost coverage, optimizes spectrum usage, and increase capacity. The 5 GHz ISM band for instance has a large swath of bandwidth available and with mobile operators looking to boost coverage, while cutting down cost, the carriers in this band are already considered as supplementary and complementary that can be aggregated with the licensed spectrum carriers to boost network capacity. But this ISM band, and as it is for most unlicensed bands, the QoE is usually unpredictable because it is shared with other technologies, including radar. This requires LBT, which is already evident in LTE-LAA (Release 13). Although LTE-LAA targeted only DL and LBT having no impact on the UE, in UL this will not be the case as UEs will be required to look for transmit opportunities before aggregating the configured radio resources with that from licensed and transmitting. In the current UE's Higher MAC coexistence coordination function block, LBT will not be limited to licensed-unlicensed UL CA, as WiFi MAC scheduler already depends on LBT to operate. It can also be extended to some of the lightly-licensed, opened for opportunistic spectrum access.

- **Duty Cycle Adaption:**

  Carrier-Sense Adaptive Transmission (CSAT) is considered an alternative to LBT in parts of the world where LBT is not required. It uses duty-cycle approach as explained in the corresponding section above, under the SC. Because CSAT is a time-domain technique, a UE has to be synchronised with the SC and therefore the ON and OFF durations have to be configured by the SC. This can be aligned with CP-DRX to optimize UE's energy consumption.

- **Frame Format:**

  Frame Format, as explained above under the SC, is to flexibly adapt the frame format according to the QoS of the different radio bearers or logical channels at the 5G-RLC, amount of traffic to be scheduled for transmission for these logical channels and the radio conditions. UEs under the control of the SC may not autonomously adapt the frame format. However, they can be configured with a selected number of frame formats, each tied to a group of logical channels. UE will then apply this frame format when multiplexing traffic from those logical channel groups.

- **Sensing Results:**

  To facilitate cooperative sensing, the UE will be configured to perform sensing of certain spectrum bands and frequency and relay the measurements to the SC. This functional block temporarily stores sensing data received from the PHY through the **S_PHY_HMAC SAP**, and if requested by the SC, forward them over the air interface. This can be periodic or on-demand sensing data.

3.2.1.3 eDSA Inter-RAT Coordination and Real-time Functions and Efficient RAT coordination

The description of this functional block at the SC also applies to the UE. Concurrency of operation of the real-time functionalities of the different RATs or AIVs are controlled by this sub-block. This is configured by the 5G-RRC through the **5GRRC_HMAC Ctrl** interface and the configuration can be semi-static. Carrier aggregation, user traffic aggregation of aggregated links, HARQ processes, and frame adaptation used by the lower MAC, will be controlled with this functional block.

- **Channel Configuration:**

  One of the underlying assumptions of this MAC framework is that there will be a large pool of radio resources from licensed, unlicensed and lightly-licensed that will be exploited to boost network capacity, reduce latency, and improve on spectral efficiency. The available carriers/frequency and bandwidth and the characteristics, are monitored and controlled by the “Carrier Configuration” functional block.

- **Heterogeneous Spectrum Aggregation:**

CA is a technique that aggregates carriers of different bandwidths in fragmented spectrum bands to increase transmission bandwidth. CA is one of the cornerstones of SPEED-5G, as the MAC framework will be presented with a large spectrum of radio resources from licensed, unlicensed and lightly-licensed bands, albeit the challenges of aggregating spectrum from bands under tighter regulations. But CA, both UL and DL are under the control of the SC. Based on the UE capabilities and with respect to supported bands, the following permutations of spectrum aggregation, but not only these, can be configured by the SC: [(licensed, licensed), (licensed, unlicensed), (licensed, lightly-licensed), (unlicensed, unlicensed)].

The “Heterogeneous Spectrum Aggregation” will coordinate the spectrum aggregation using the different lower MAC schedulers, as configured by the SC.

- **Multi-Access Coordination:**

This will not be further elaborated, as it is already described at the SC. The description applies equally to the UE.

- **RACH Coordination:**

Random Access is one of the first procedures performed by a device which wants to establish an active connection with the SC. As described at the SC, the procedure can be contention- or non-contention-based. Lower MAC LTE-A and WiFi schedulers have their own RA schemes and 5G-AIV scheduler will have a different scheme fitting to the constraints of the spectrum band of operation. From the UE side, the coordination of the RA procedures depending on if the spectrum band is being shared across the different Lower MAC schedulers will be coordinated by the “RACH Coordination” functional block.

- **Control Traffic Coordination:**

A UE that supports multiple RATs can be configured to transmit control messages on multiple AIVs. This can effectively introduce redundancy, yet reliability in sending the control messages. For example, UEs at cell edges will be experiencing high interference and this redundancy (sending same control on multiple AIVs) can be used to reliably send control messages to attached SC. The coordination of this control traffic, based on radio condition, will be handled by the “Control Traffic Coordination” functional block.

- **Load Balancing:**

Load balancing is a typical SC functionality. However, there is some demand for certain devices to complement load balancing by using some rules configured by the SC. The different lower-MAC schedulers are expected to operate concurrently and with the load balancing rules, traffic of certain QoS can be offloaded through different AIVs in UL. These rules can also be applied to D2D, where and based on the network load, communication can be offloaded off from the network, by creating direct communication among devices in close proximity.

3.2.2 Lower-MAC

The lower-MAC functionalities have been well introduced at the SC section above. The Lower-MAC comprises of two main functionalities: scheduling coordination and (de-)multiplexing and (dis-)assembly.

In the UE, the lower-MAC block interfaces with 5G-RLC through **C_5GRLC_LMAC SAP** and **D_5GRLC_LMAC SAP**. The Lower-MAC is the only termination point for 5G-RLC interface. Between Lower MAC and the 5G-PHY, the communication is through **C_LMAC_PHY SAP** and **D_LMAC_PHY SAP** interfaces. The interfaces have been described at the SC and apply equally to the UE.

The Lower-MAC houses all the supported AIVs, such as LTE-A, WiFi and 5G-AIV. To synchronise with the SC description, the lower-MAC 5G-AIV will be the focus below.

3.2.2.1 5G-AIV Scheduling Coordination function blocks

The lower-MAC 5G-AIV is the scheduling coordination and transmission and reception capabilities of the UE, as it is also for the SC. It is supposed to push the network capacity and spectral efficiency to the limit by adapting novel techniques, such as NOMA and CA, to optimize radio resources usage.

The **Scheduling Coordination** block consists of**:**

- **Logical Channel Manager:**

  In the UE, the Logical Channel Manager manages the different logical channel groups at the 5G-RLC layer. Each logical channel has a certain QoS, requiring different transmission techniques, flow control, error correction and etc. In UL, prioritisation of logical channels in every transmit opportunity is managed by the Logical channel manager.

- **Coexistence Scheduler:**

  This will not be further elaborated, as it is already described at the SC.

- **Carrier Configuration:**

  The lower-MAC Scheduling Coordination is real time. The number of supported bands of a device can be scaled down to its underlying service requirements. For example, cheap Lower-end IoT devices might support at most one or two bands, and with their intermittent traffic transmission pattern; the supported bands could for instance, be lightly-licensed spectrum band. Some devices could support a mixture of these bands for reliability. The real time changing of the channels of these supported bands will be controlled by the SC, based on the UE’s measurements, but the coordination in the UE will be handled by the “Carrier Configuration” functional block.

- **QoS:**

  This will not be further elaborated, as it is already described at the SC. In the UE, this functional block is tightly coupled with the “Logical Channel Manager”.

- **Ctrl:**

  This will not be further elaborated, as it is already described at the SC.

- **Frame:**

  This will not be further elaborated, as it is already described at the SC.

3.2.2.2 5G-AIV TX/RX function blocks

The data plane traffic transmission and reception are managed by the “TX/RX 5G-AIV” functional block. Under the constraints of the “Scheduling Coordination” functionalities, the “TX/RX 5G-AIV” manages the amount of traffic that is transmitted for example, in UL, in every TTI or TxOp.

- **(De-)Multiplex:**

  The messages that can be transferred from MAC to the peer MAC in SC are 5G-RLC’s traffic (control and data), MAC control signals, and sensing results. Each of these data has certain priorities based on a predefined rule or dynamically configured by the SC. Meeting the TB size at each TTI or TxOp, would require multiplexing available logical channels with varying QoS, taking into considerations their priorities. The same goes in DL, where TB is de-multiplexed and the group of data (5G-RLC logical channel traffic, MAC control messages) are distributed to the appropriate functional blocks for further processing.

- **(Dis-)Assembly:**

  This will not be further elaborated, as it is already described at the SC.

3.3 Examples of High-level MAC procedures for eDSA support

The functional block diagram described in the section 3.1 shows a complex functional architecture of the MAC layer, built on higher-MAC and lower-MAC sub-parts, with many blocks and interfaces related to control, monitoring, and data planes. This section provides a high-level description of main functional blocks, based on example procedures required to enable eDSA.

3.3.1 Supplemental carrier configuration at MAC level

The following procedure corresponds to the situation in which the MAC layer is requested to identify a channel for hosting a supplemental component carrier after a decision is taken at the cRRM level to offload a set of logical channels. Figure 6 illustrates this procedure with the sequence of messages involved in this procedure, corresponding to communications between functional blocks of Figure 2.

Prior to this procedure, the situation is the following: at small cell level, a number of radio interfaces are switched on and are currently taking care of active logical channels with a satisfactory level of QoS. For some reason the capacity of the active air interfaces is not able anymore to support the active logical channels (for example, admission of a new logical channel, degradation of the level of interference on a given air interface) and cRRM decides to proceed to load balancing and asks the MAC to eventually steer some traffic on a supplemental carrier of 20 MHz band on the 5GHz band (for instance). The cRRM may have prior information on this band thanks to sensing operations done in the past which could have made possible the construction of channels quality indicators on this band. If the last update on those indicators has been done before an obsolescence limit (which is beyond the scope of this document), the status of the 5 GHz band is considered as unknown. The following procedure starts with a command sent by cRRM to MAC layer asking to identify a channel and ends with an acknowledgement (or NACK) of the MAC once the channel has been identified and lower MAC and PHY have been configured.

The detail of the procedure is given here, highlighting the key messages of the procedure, using the numbers appearing as labels on the MSC of Figure 6.

- Message 1 is sent by cRRM to the higher MAC, and more specifically to the “Load balancing” block via the 5GRRC-HMAC interface, which is forwarded to the “coexistence coordination” entity with a channel identification request. This request triggers an “RX_on” request to the PHY.
- Once done, the coexistence coordination entity, via the “sensing coordination” block gets from the cRRM (messages 5 and 6) the needed parameters: channel bandwidth, CCA threshold, sensing mode (energy detection, min-max), sensing duration and the preferred channels, if any.
- Thanks to the message 7, the “sensing coordination” block of the higher MAC requests the sensing along with the sensing parameters to the PHY which in return sends the measured RX powers on the different channels (either on the preferred channels or on the whole band). These RX powers are compared with the CCA threshold by the sensing coordination blocks
- If no channels are found as available, the higher MAC sends to cRRM an indication of this situation and the procedure stops; this requires that cRRM asks for the same procedure on another band (messages 9 and 9bis).
- If some channels are found available, the sensing coordination blocks sends to the load balancing block the list of those channels and one of them will be chosen, according to a selected algorithm (multi-armed bandit, random process for instance). Once done, the higher MAC, via the “channel configuration” block sends a request to the lower MAC to configure

the scheduler and PHY accordingly (messages 12 to 15) and confirms to cRRM when this is complete.

- In parallel, the “sensing coordination” block provides the “KPI/measurement management” entity with the updated RX powers on the sensed channels, which will be stored on the “sensing results” block (message 11).
- Once the cRRM is notified that the channel selection is complete, it sends to the lower MAC (message 17) the required parameters for configuring the frame (LBT parameters, TxOp policy) and the CCA threshold. The frame format block at higher MAC level sends a request to configure the scheduler at lower MAC level accordingly.
- When this is done, cRRM is notified that the procedure is successfully completed.

Optionally, cRRM can send a measurement report request to the “KPI/measurement management” entity to get the updated RX powers on the sensed bands (message 21 and 22).

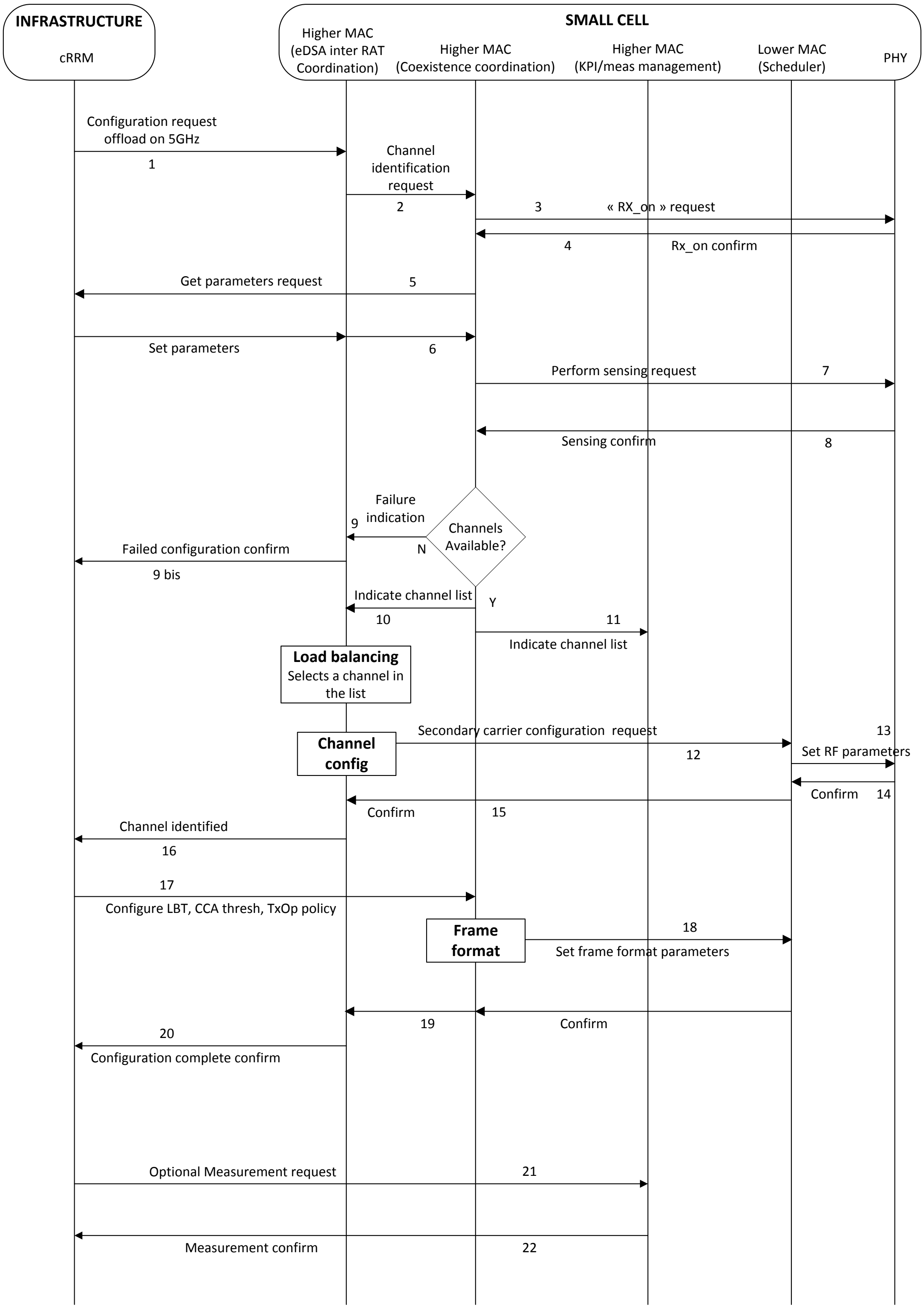

Figure 6: Supplemental carrier configuration at MAC level

3.3.2 Control traffic offloading at MAC level

The following procedure corresponds to the situation in which the MAC layer decides to offload control traffic transmitted over a RAT operating in an unlicensed band due to a high level of interference which reduces the reliability of control information exchange. Figure 7 illustrates this procedure with the sequence of messages involved in this procedure, corresponding to communications between functional blocks of Figure 2.

The preconditions describing the status of the network, before the described procedure is initiated are: UE and BS are connected over RAT1 and RAT2 and are actively using both radio interfaces to exchange user and control data. RAT1 operates in a licensed band and RAT2 operates in an unlicensed band. BS and UE know which control channels can be offloaded from RAT2 to RAT1 (this knowledge can be obtained during the connection setup). The sensing and measurements management functions in BS and UE are configured to collect control channel quality information. The measurements collected by the sensing and measurements management functions are continuously monitored by the Control Traffic Coordination block located in the Higher MAC on BS and UE side.

The following procedure is initiated when a significant degradation of control channel quality is detected by the Control Traffic Coordination block located in Higher MAC on BS or UE side. The detail of the procedure is given below using the numbers appearing as labels on the MSC of Figure 7.

- Step 1: Control Traffic Coordination function on the BS side detects the drop in the control channel quality of RAT2 by detecting a significant drop in the SINR (or increase in frame error rate) measured for the control channels. Control Traffic Coordination function decides that RAT1 should take over transmission of control traffic conveyed over RAT2 to increase the reliability of control data and prevent degradation of user data exchange over RAT2.
- Step 2: An internal message is sent from Control Traffic Coordination function located on the BS side to Lower MAC of RAT2 to release resources reserved for the affected control channels.
- Step 3: Time/Frequency Domain scheduler in Lower MAC releases resources reserved for transmission of the affected control channels. Optionally, the reconfiguration of the frame structure takes place to reduce the amount of resources allocated for control traffic.
- Step 4: An internal message is sent which confirms successful release of resources by RAT2 scheduler.
- Step 5: An internal message is sent from Control Traffic Coordination function to Lower MAC of RAT1 to trigger reservation of resources for transmission of RAT2 control traffic.
- Step 6: The behaviour of Time/Frequency Domain scheduler in RAT1 is modified to provide sufficient resources and QoS for transmission of control traffic offloaded from RAT2. Optionally, the reconfiguration of the frame structure takes place to better accommodate changes in traffic load over RAT1.
- Step 7: An internal message is sent which confirms successful reservation of resources by RAT1 scheduler
- Step 8: Control Traffic Coordination function in BS redirects RAT2 control traffic to RAT1 interface.
- Step 9a/9b/9c: RAT2 Control message along with the re-configuration information for the UE Higher MAC is transmitted over RAT1 and received by Control Traffic Coordination function located in the Higher MAC on the UE side.
- Step 10: Control Traffic Coordination function in UE side processes RAT2 Control message and using the received re-configuration info it initiates control traffic offloading procedure to redirect control traffic from RAT2 to RAT1.
- Step 11a-11f: In case resources for control traffic in RAT2 are not released and additional resources in RAT1 are not reserved (in some situation the release of resources on the UE side may be indirectly triggered by Step 3 and reservation by Step 6), Steps 2-7 are repeated on the UE side.
- Step 12: Control Traffic Coordination function in UE redirects control traffic of RAT2 to RAT1.

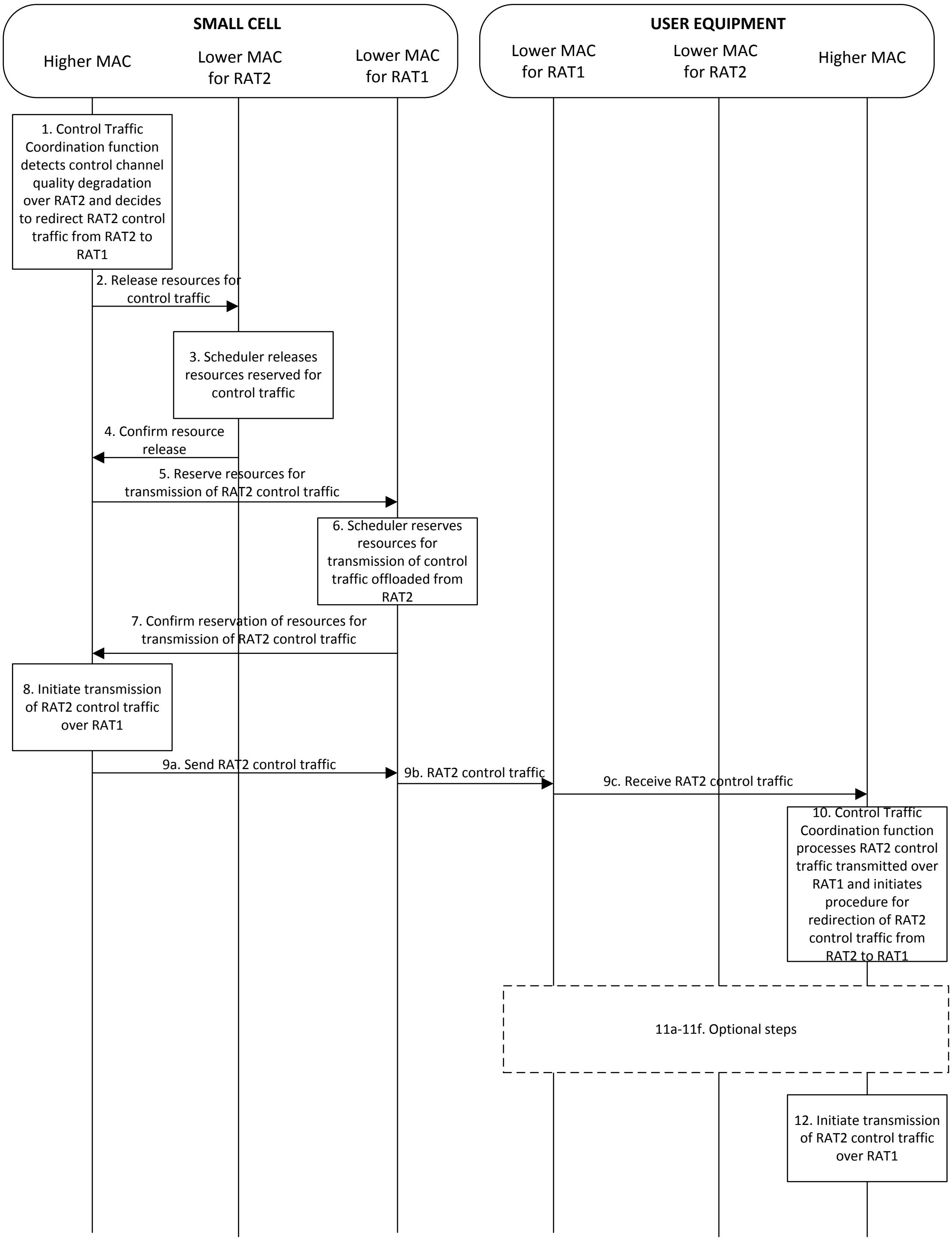

Figure 7: Control traffic offloading at MAC level

3.4 Summary

This chapter has presented the SPEED-5G MAC framework, functional components and the new U/C/M-plane interfaces, in order to support the eDSA. Some examples of high-level MAC procedures for eDSA support are also presented and analysed. following this high-level introduction, the next chapter presents a number of distinct MAC designs that are incorporated into (and supported by) the proposed MAC framework.

4 MAC designs for eDSA

This chapter describes different MAC designs supported by the SPEED-5G MAC framework. The main features of the proposed MAC designs are:

- **MAC design #1** – a MAC design, based on ECMA standard [20] with novel extensions to support mIoT and xMBB, tightly integrated with a FBMC PHY, operating in unlicensed bands.
- **MAC design #2** – a MAC design based on LTE [46] and LTE-LAA [43] standards, with additional support for massive-IoT (mIoT), operating in licensed and unlicensed bands.
- **MAC design #3** – a new waveform-independant MAC design based on dynamic channel selection, capable of operating in licensed, unlicensed and lightly-licensed bands.

The MAC algorithms have been designed to operate in mutli-RAT environments under a variety of spectrum regimes. All the MAC algorithms designed to natively support the SPEED-5G virtualized architecture defined in [2]. The “new” MAC algorithm, is additionally capable of operating autonomously without the information of spectrum characteristics, to cover the case when the small cell can’t rely on the SPEED-5G virtualized architecture.

4.1 MAC design #1: FBMC MAC operating in unlicensed spectrum

This section reports the design and orchestration of blocks involved in the access of a radio bearer on an unlicensed band, assuming a FBMC PHY. Compared to the state of the art of PHY/MAC systems, based on FBMC ([28]), this design supports use of FBMC physical layer and different QoS classes, while complying with the European regulation. This section starts with the relation to the SPEED-5G MAC block diagram, shown on Figure 2, highlighting the functions this design is relying on, for both higher and lower-MAC levels. It continues with the assumptions made on the PHY layer and describes how the access is managed for two kind of traffic type: mIoT and xMBB. The two access schemes will be validated on a system level simulator using synthetic and realistic scenarios, this deliverable, in section 5.1, providing results obtained on the design tailored for IoT traffic. Also, MAC layer will be implemented in Task 5.3 on a custom HW platform where FBMC is running.

4.1.1 Relation to the MAC Framework

The mapping of the MAC design described in this section related to the SPEED-5G MAC framework (of figure 2), is depicted in Figure 8 below, highlighting the considered impacted functions by means of colouring them in black.

On the higher MAC level, in addition to the "sensing and measurement management" entity which is mandatory to enable the cRRM coordination, this FBMC MAC relies on all the blocks of the "coexistence coordination” entity. Indeed, this MAC protocol is designed to operate in shared spectrum, which requires the adequate means to cope with the regulation constraints in one hand (duty cycled activity, listen before talk for instance) and with the varying SINR conditions in the other hand. The latter can be mitigated by adapting the frame format to facilitate the coexistence with neighbouring systems. Moreover, this MAC design is genuinely mixing contention and scheduled access schemes and transmit opportunities determination on lower MAC level shall have to be coordinated by the higher MAC, adapting for instance the CSMA-CA algorithm to the traffic conditions or the number of active devices (number of CCA tries, backoff policy for instance).

Still on the higher MAC, in addition to the channel configuration, heterogeneous resource aggregation and load balancing functions which are key features of eDSA, this MAC design requires the “MA coordination” function to tune PHY/MAC parameters having an impact on the multiple access performance like frame numerology, prototype filter depth or guard band width between adjacent channels or resource block allocations. Finally, the “frame format” block is required as well since the FBMC MAC design is built on configurable frame format with scheduled or contention based periods which can be adapted, depending on the traffic QoS requirements or number of active devices.

On the lower MAC level, most of the blocks of the 5G-AIV components are active except CP-DRX, which is not supported in this design.

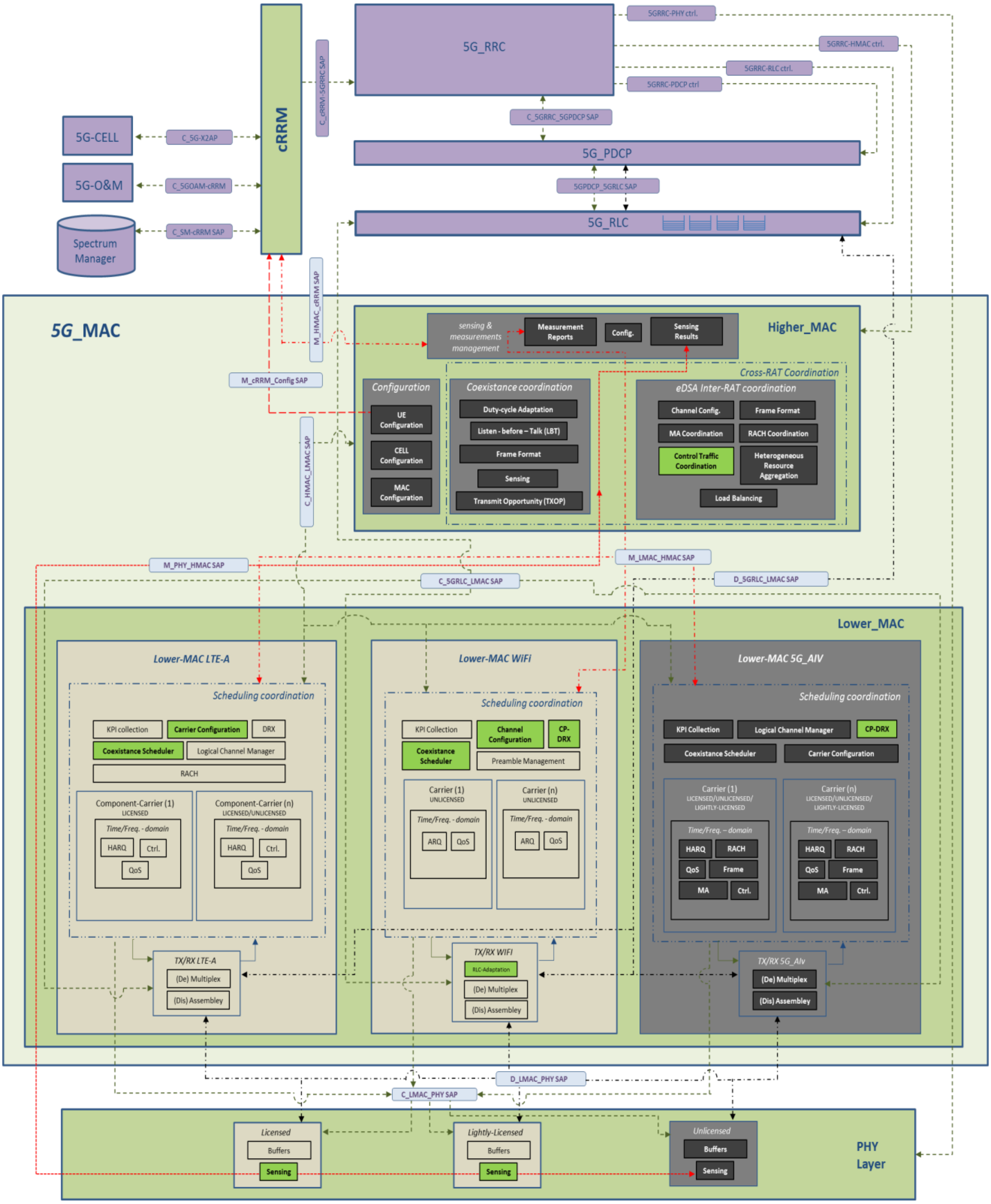

Figure 8: Functional blocks used by the MAC design #1 (SC-side)

For the UE side, depicted in *Figure 9*, the blocks involved in this MAC design are the same as at the small cell side, except the frame format adaptations in the higher-MAC, since this operation is taken in charge by the small cell.

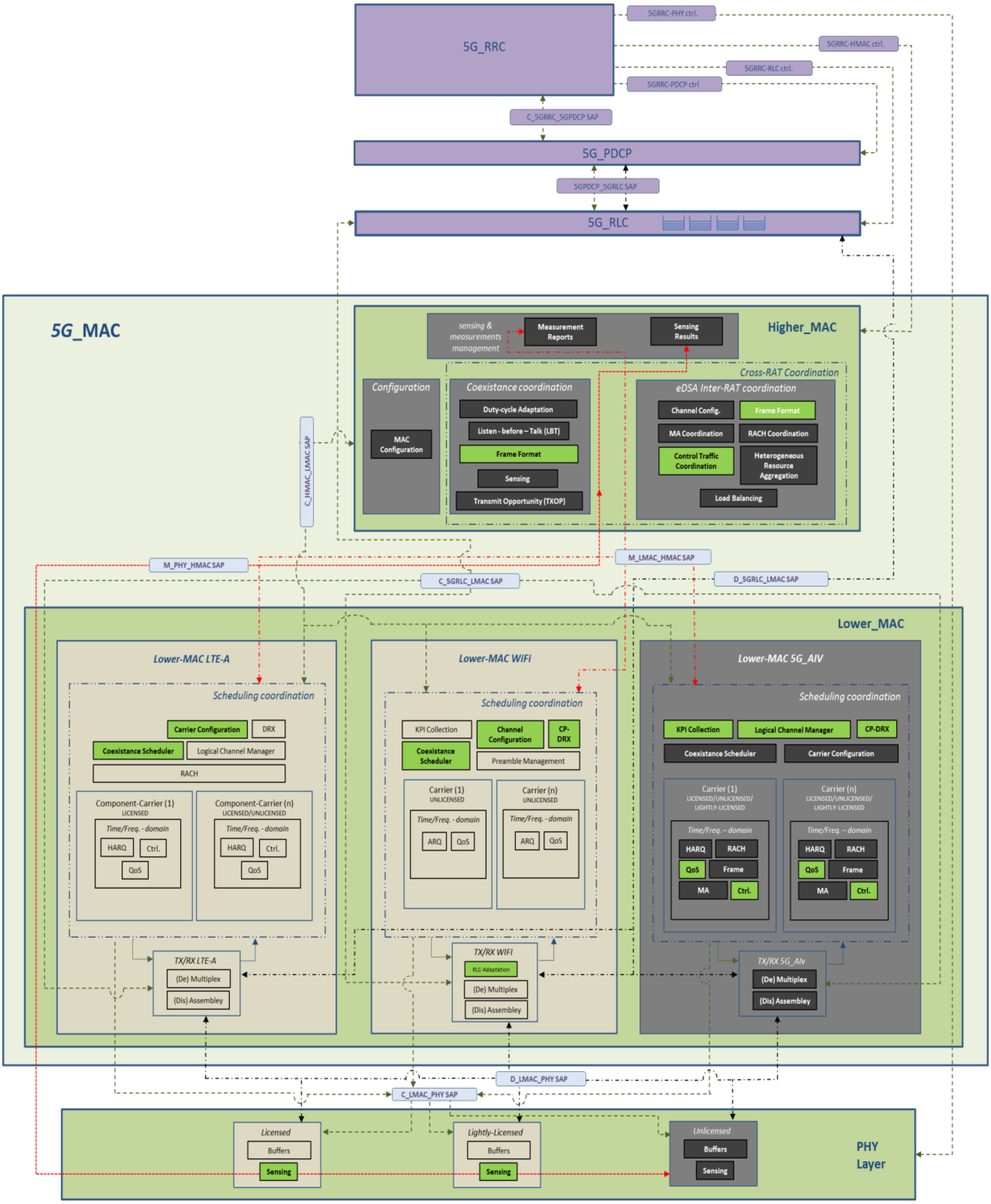

Figure 9: Functional blocks used by the MAC design #1 (UE-side)

4.1.2 Physical layer Considerations

FBMC was originally introduced in the 1960s [8]. It is a multi-carrier modulation, but unlike Cyclic Prefix based Orthogonal Frequency Division Multiplexing (CP-OFDM) where the sinc kernel filter ensures subcarrier orthogonality with respect to the FFT operation, FBMC uses a prototype filters that filters each subcarrier. A proper design of the prototype filter enables to trade time and frequency localization, and thus to control adjacent carrier leakage ratio (ACLR). Because the prototype filter's response spreads each subcarrier over several adjacent subcarriers, another dimension is used to 'restore' orthogonality. In the frame of this project, the offset QAM (OQAM) approach is considered. OQAM consists in a complex to real conversion where real and imaginary parts of each complex symbol are multiplexed in consecutive time samples into Pulse Amplitude Modulation (PAM) symbols (Figure 10). In order for this pre-processing not to impact data rate, the PAM symbols are up-sampled by a factor of 2.

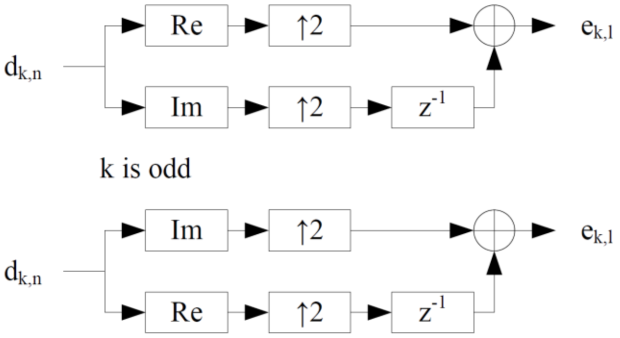

Figure 10: OQAM pre-processing in FBMC transmission chain

Then, the output real numbers are multiplied by an offset QAM sequence to form a new complex symbol: $h_{k,l} = (-1)^{kl}(j)^{k+l}e_{k,l}$. These symbols are consequently filtered through a polyphase network *G(z)*. The FBMC modulator and demodulator are shown in Figure 11.

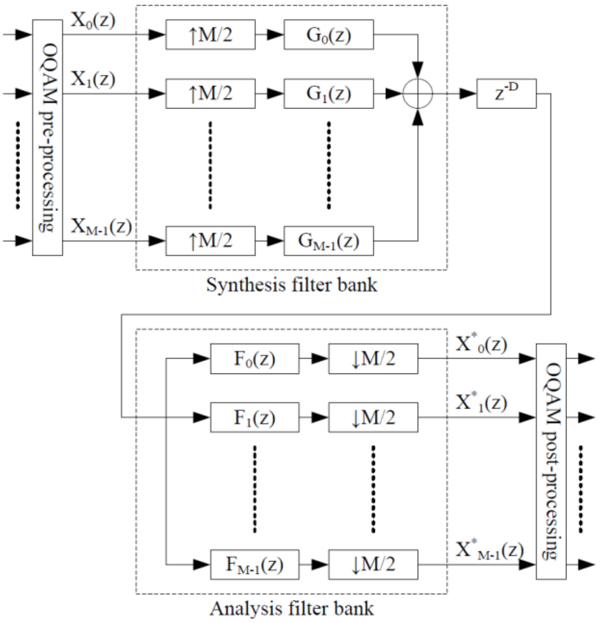

Figure 11: FBMC modulator and demodulator

The depth *K* of the prototype filter governs the level of adjacent channel leakage (ACL), like shown in Figure 12, where FBMC waveform frequency localisation can be compared, for several values of *K*, with genuine (CP-)OFDM and another waveform called Universal Filtered Multicarrier (UFMC) [27]. On this figure, on can observe that the leakage on the adjacent channel is as high as -13 dBc for OFDM, whereas it can be as low as -60 dBc for FBMC for *K*=4.

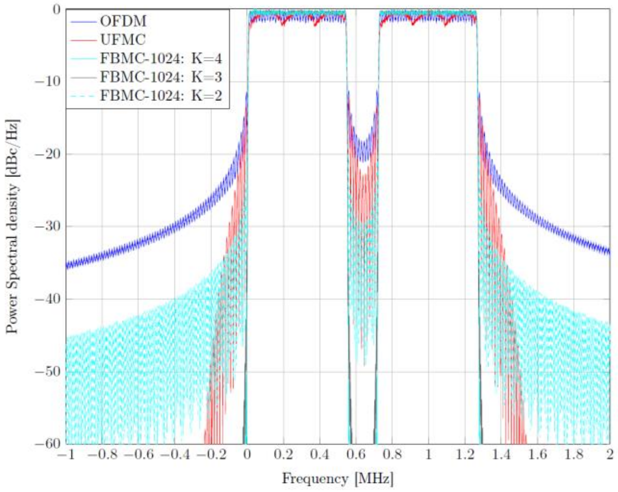

Figure 12: Power spectral density of OFDM, UFMC and FBMC-OQAM with several values of K.

Compared to OFDM, this excellent spectral localisation of FBMC signal implies a set of characteristics a MAC layer can exploit to optimize the medium access:

- **Relaxed synchronicity**: multi-user communications in CP-OFDM require a very tight synchronisation to avoid inter-carrier interference. Indeed simultaneous transmissions in contiguous bands have to respect a timing misalignment smaller than the cyclic prefix length. In comparison, FBMC can gracefully tolerate asynchronous communications, because of the very small of adjacent carrier interference. In terms of MAC design, this means that UL FBMC communications could be set-up in such a way that devices can transmit on contiguous bands, without being synchronised.
- **Reduced guard band**: Thanks to its very low ACLR, it has been shown in [9] that FBMC can tolerate a very small guard band, compared to other multi-carrier waveforms as one inter-carrier spacing suffices. The MAC layer can thus manage in an efficient way the allocation of (thin) resource blocks, even if they are fragmented and spread in the band. When coupled with the previous feature, this offers the capability of efficiently using the band.
- **Relaxed uplink power control**: Along the same idea of very low ACLR, the UL signal in contiguous bands can be transmitted without a strict power control. Indeed, provided that ACLR is more than 60 dB, two simultaneous signals on contiguous channels can arrive on a SC with a very large difference of UL received power.

More details about the FBMC modulation and the filter coefficients can be found in [10], whereas implementation issues are presented in [11]. **The remainder of the section presents the PHY options selected and then the MAC designs for both IoT and broadband traffic operating in unlicensed spectrum are presented.**

4.1.2.1 Narrowband FBMC physical layer description

This section provides various aspects of PHY specifications for IoT devices operating in the 868 MHz frequency band based on a FBMC scheme. It is worth mentioning that this work is not addressing the lowest end of IoT devices, requiring a very low data rate (e.g., lower than 1 kbps) with an extremely simple channel access scheme.

Considered spectrum band - The operating band of the network is the 868 MHz ISM band, in which different systems may exist. In this shared band a low channel bandwidth is generally available; therefore the devices can operate in this band while respecting the regulatory requirements [12]. In this work, we consider that the whole system will be operated on a 3 MHz wide carrier, located in the 865-868 MHz band. In this band, the regulatory requirements specify that the end-devices may transmit on any available channel at any time through respecting a maximum transmit power of 25 mW and a duty cycle < 1%.

Channel coding - A convolutional code with constraint length 7 and 1/2 coding rate (generator polynomials are 171 and 133 in octal) is used. Tail bits of length 8 are added at the end of the input stream to force the encoder to its "all 0" initial state. For other code rate (R = 2/3, 3/4, 5/6), puncturing can be performed based on the mother convolutional code of rate 1/2.

Modulation and coding scheme - The binary input is converted into complex symbols using Gray-coded constellation mappings. The supported modulations include BPSK, QPSK, 16-QAM and 64-QAM. Various MCS considered in the IEEE 1900.7 standard can be found in Table 6 in [28].

The amount of information that can be sent within a slot depends on the slot duration and the MCS used. The available MCS ranges from MCS0 to MCS7 and their corresponding data rates range from 86 kbps to 874 kbps (for a packet payload size of 0 - 200 bytes). In case of beacon, control and command frames; the MCS 1 (QPSK, coding rate 1/2) should be used. Data and corresponding acknowledgement (ACK) frames must be transmitted using the same MCS (the one specified for data frame).

Table 6: Narrowband modulation and coding schemes

MCS	modulation	coding rate	data rate (Kbps) [3]
0	BPSK	1/2	[86- 90]
1	QPSK	1/2	[167- 179]
2	QPSK	¾	[243-268]
3	16-QAM	1/2	[314-356]
4	16-QAM	3/4	[443-530]
5	64-QAM	2/3	[557-703]
6	64-QAM	3/4	[627-788]
7	64-QAM	5/6	[667-874]

Modulation parameters - The maximum number of subcarriers (N) is set to 64 with an inter-carrier spacing Δf of 60 kHz. The stream of complex symbols is divided into groups of N_c complex symbols, where $N_c$the number of non-null modulated subcarriers (active subcarriers). FBMC modulation is then applied at the transmitter and at the receiver, where a preprocessing step (complex-real conversion), a filtering step and a sum-overlap step are carried out. The transmitted time of FBMC signal depends on the overlapping factor (K), the number of FBMC symbols (N_{symb}) and the number of subcarriers (N) : $T_{\text{signal}} = (KN + \left(2N_{\text{symb}} - 1\right)\frac{N}{2})/F_{\text{s}}$, where F_{s} is the sampling frequency which is equals to F_{s} = $N\Delta f$ = 3.84 MHz.Table 7 shows the parameters for FBMC modulation retained in the case of IoT traffic operating in the 868 MHz band.

Table 7: Narrowband FBMC parameters

Parameters	value / subband	value/ total Band
N	64	64
N_{c}	3	48
Δf	60 kHz	60 kHz
K	4	4
Bandwidth B	180 kHz	2.88 MHz
$F_{\text{s}} = N\Delta f$	3.84 MHz	3.84 MHz

---

[3] Data rate depends on the packet payload size. It has been computed for 0-200 bytes.

4.1.2.2 Broadband FBMC physical layer description

This PHY mode can be used in any spectral chunk where 10 MHz and 20 MHz carriers can be allocated; for instance 5GHz, 3.5 GHz, 2.3 GHz bands could be suited for this configuration. Note that the TVWS scenario is a particular case, due to the sharing with TV broadcasting signal characteristics. Indeed, channelization shall be similar to the TV multiplex bandwidth, meaning 8 MHz band in Europe and 6 MHz in the US. The interested reader can refer to [1] to get a detailed specification of the IEEE 1900.7 standard, which is based, on an 8 MHz FBMC physical layer. This subsection provides the specification of a 10 MHz and 20 MHz configuration of the FBMC physical layer, which is assumed for broadband communications.

Modulation and coding scheme - The binary input is converted into complex symbols using Gray-coded constellation mappings and the supported modulations are QPSK, 16-QAM, 64-QAM and 256 QAM. The channel coding process relies on a set of two possible coding options which are turbo or convolutional coding of rate 1/3, like for the LTE physical layer in downlink [13]. After the channel coding stage, rate adaptation is applied, leading to a wider range of actual coding rates [13]; we assume that rate adaptation leads to coding rates of 1/3, 1/2, 2/3, 3/4 and 5/6. Modulation and coding scheme is adapted during the communication so that throughput of devices is maximized when the channel conditions they experience are good. In the same way it is done in LTE, this is made possible by means of measuring the SINR on reference signals and reporting the CQI to the SC. The definition of reference signals are beyond the scope of this document (one can refer to [13] to get a description of the LTE procedure). Assumption is made that data packets are turbo-coded whereas control (short) packets (beacon, CQI updates, transmission requests) are coded using the convolutional coder. Table 8 shows the different MCS available for 10 MHz and 20 MHz bands. Because of the effect of the prototype filter (*K* factor), the actual throughput of a FBMC link depends on the number of bits the packet contains. InTable 8, we give the asymptotical throughput obtained for a packet of an infinite length.

Table 8: Modulation and coding schemes of FBMC PHY for 10 MHz and 20 MHz bands

MCS	modulation	coding rate	efficiency	throughput 10 MHz (Mbps)	throughput 20 MHz (Mbps)
0	QPSK	1/3	0.67	6.04	12.04
1	QPSK	1/2	1.00	9.06	18.06
2	QPSK	2/3	1.33	12.08	24.08
3	QPSK	3/4	1.50	13.59	27.09
4	QPSK	5/6	1.67	15.1	30.1
5	16-QAM	1/3	1.33	12.08	24.08
6	16-QAM	1/2	2.00	18.12	36.12
7	16-QAM	2/3	2.67	24.16	48.16
8	16-QAM	3/4	3.00	27.18	54.18
9	16-QAM	5/6	3.33	30.2	60.2
10	64-QAM	1/3	2.00	18.12	36.12
11	64-QAM	1/2	3.00	27.18	54.18
12	64-QAM	2/3	4.00	36.24	72.24
13	64-QAM	3/4	4.50	40.77	81.27
14	64-QAM	5/6	5.00	45.3	90.3

15	256 QAM	1/3	2.67	24.16	48.16
16	256QAM	1/2	4.00	36.24	72.24
17	256QAM	2/3	5.33	48.32	96.32
18	256QAM	3/4	6.00	54.36	108.36
19	256QAM	5/6	6.67	60.4	120.4

Modulation parameters - In this work, we assume to rely on a particular implementation of FBMC called Frequency Spreading-FBMC (FS-FBMC) [11]. Performance study shows that this implementation allows reaching the same level of performance of the ULPHY of LTE (based on Single Carrier (SC)-FDMA) even when the number of sub-carriers is reduced by a factor of 4. In other word, if the 10 MHz option of LTE is based on 1024 sub-carriers and an inter-carrier spacing of 15 kHz, an “equivalent” FBMC PHY would be based on a 256 carriers with a 60 kHz inter carrier spacing. As a consequence of this subcarrier number reduction, the Peak-to-Average Power Ratio (PAPR) obtained with the FBMC-256 is similar to the SC-OFDM, meaning that we can use the same modulation scheme for both the UL and the DL, which is another very interesting feature of FBMC for MAC design.

Table 9 shows FBMC parameters for broadband transmission for a total bandwidth of 10 and 20 MHz. A key feature of FBMC, like other filtered multi carrier modulations, is that two asynchronous transmission on adjacent channels or bands yield to no significant impact in terms of interference provided a guard band equal to an inter-carrier spacing is introduced. It translates into a better spectrum occupation, since in our case a 10 MHz band is fully occupied with active subcarriers, except 1 subcarrier (as a guard band). Compared to LTE, this provides a spectrum efficiency improvement of approximately 10 %. This feature will be further exploited for resource allocation in uplink, given the subcarrier guard band is inserted between 2 concurrent and adjacent emissions.

Table 9: Broadband FBMC parameters

Parameters	10 MHz band	20 MHz band
N	256	512
N_c	165	330
Δf	60 kHz	60 kHz
K	4	4
Bandwidth B	9.9 MHz	19.8 MHz
$F_s = N\Delta f$	15.36 MHz	30.72 MHz

4.1.3 MAC design #1a: MAC design for IoT traffic operating in the 868 MHz band

This section outlines the main PHY and MAC assumptions considered for IoT systems operating in the 868 MHz band. In particular, PHY assumptions based on FBMC techniques are first described. Traffic patterns and device classes are next presented to support the requirements of IoT systems. Then MAC layer design is considered in order to support the different device classes.

The MAC layer design has been derived based on ECMA-392 standard [20] that specifies a contention-based and reservation-based channel access mechanisms along with others functionalities [15]. In particular, the MAC layer has been simplified and modified to support multi-band access. The main functionalities retained for IoT traffics are:

- A reservation-based channel access mechanism,
- A contention-based channel access mechanism.

A network operates in master-slave mode. In the master-slave mode, a device is designated as master (also referred to as network coordinator or SC in case of cellular context) and others are associated with the master as slaves. The master coordinates channel access in the master-slave mode. Communication is normally established between slave devices and the master device. The SC transmits beacon frames to provide the basic timing for the network and to carry reservation and scheduling information for accessing the medium. These beacon frames allow advertising the SC presence, and synchronizing the devices.

The reservation-based channel access mechanism consists to dynamically allocate a set of resources in a contention-free period based on a previous negotiation. An efficient scheduling mechanism must be therefore developed for flexible resource utilization. Meanwhile, the contention-based channel access mechanism allows devices to contend in order to get access to the medium; the device can either send a reservation request or a data packet**. In addition to basic features the following new features have been integrated into the proposed MAC design**:

- packet retransmission mechanism
- Support for power-saving mode
- mIoT support in unlicensed band.

4.1.3.1 MAC Services

4.1.3.1.1 Services provided to upper layers

In addition to services already supported in [20], a number of new services (in Bold) are provided by the extented MAC design to upper layers, mainly related to the support of IoT communication:

- data transfer **using multi-channel operation**
- radio resource allocation, **depending on the traffic patterns**

4.1.3.1.2 Services expected from physical layer

The physical layer services provided to the MAC sublayer are mostly as identified in [20], but also new services (in Bold):

- **Multichannel uplink and downlink transmission**
- Frame transmission for both normal and burst modes;
- Frame reception for both normal and burst modes;
- Header error indication for PHY and MAC header;
- Clear channel assessment for estimation of medium activity.

4.1.3.2 MAC Functions

In addition to functions identified in [20], a number of new functions (in Bold) are supported by the extended MAC design:

- A reservation-based channel access mechanism;
- A prioritized, contention-based channel access mechanism;
- Priority handling between UEs by means of dynamic scheduling;
- **Adaptative frame format on traffic requests**
- **Mechanisms to comply with the ETSI regulation on 868 MHz band** ;
- Device power management by scheduling of frame transmission and reception;
- **ACK management for both scheduled and non scheduled tranmission**
- Logical Channel prioritisation;
- **Low power downlink transmission with bounded latency**

The location of all functions and their relevance for uplink and downlink respectively is illustrated in Table 10 (new functions are highlighted in Bold)

Table 10: *MAC function location and direction association for design #1a*

MAC function	UE	eNB	Downlink	Uplink
A reservation-based channel access mechanism	X		X	X
		X	X	
A prioritized, contention-based channel access mechanism	X			X
		X	X	
Priority handling between UEs by means of dynamic scheduling				
		X	X	X
Adaptative frame format on traffic requests		X	X	X
Mechanisms to comply with the ETSI regulation on 868 MHz band ;		X	X	X
Device power management by scheduling of frame transmission and reception		X	X	X
ACK management for both scheduled and non scheduled tranmission	X		X	
		X		X
Logical Channel prioritisation;		X	X	X
Low power downlink transmission with bounded latency		X	X	

4.1.3.3 Protocol Details

This section provides information on the proposed MAC protocol design and operation.

4.1.3.3.1 Frame Design and Structure

The basic timing structure for frame exchange is a superframe. The superframe duration is specified as *mSuperframeDuration*. The superframe is composed of 512 medium access slots (MASs), where each MAS duration is *mMASDuration* (Figure 13).

As shown on Figure 13, each superframe starts with a beacon period (BP), which extends over one MAS. A recurring superframe consists of a beacon period (BP), a data transfer period (DTP) and an inactive period. The DTP is divided into contention-free period (CFP) and contention access period (CAP).

The length of CFP and CAP is adjustable and depends on the network traffic type and density. e.g., CFP can be used in the case of small portion of devices, while CAP can support a large number of devices. This allows a scalable and flexible structure for a dense heterogeneous IoT network.

It is worth mentioning that the beacon frame is transmitted over the total band with MCS1, while the data and others command/control frames are transmitted in sub-bands during DTP. We assume that the devices are able to decode the beacon and to subsequently obtain the information over all the sub-bands by performing fast Fourier transform (FFT) operation on the received beacon frame.

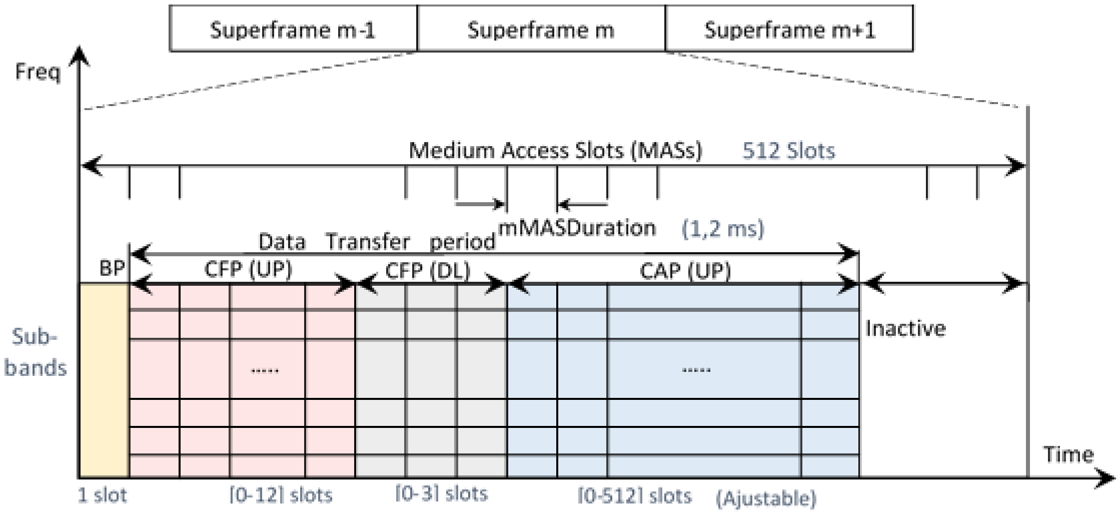

Figure 13: Superframe structure

4.1.3.3.2 Multiple Access

Depending on the application requirements, the medium can be accessed in different ways:

- During the BP, the SC sends only beacon frames, spanning on the whole band, with a total number of active carriers equal to 48 (cf. Table 7).
- During DTP,
  - Access is managed on a sub-band basis; each sub-band is composed of 3 active carriers and one inactive carrier as a guard band. The sub-band bandwidth is therefore 180 kHz, as shown on Table 7
  - In CFP, devices participating in the reservation send frames, where the scheduling may be negotiated within a reservation request.
  - In CAP, the devices contend for access to the medium to send data traffic (report) or to send reservation request to the SC trying to reserve a dedicated resources for data transmissions in the next superframe. Based on the received request and resources availability, the SC notifies the corresponding devices about the dedicated resources in the beacon frame in the next superframe.
- During inactive period, all devices keep silent.

Periodic reporting: when a device has a report to send, the device first wakes up at the corresponding reporting interval, and then it performs beacon synchronization and contends to access the medium. A multiband Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) algorithm can be used to contend to the medium for channel access both in time and frequency domains [16]. The packet emission can be done along the two following options:

- Request for a transmission grant (sensitive data): During the CAP, the device transmits a transmission grant request. If there are sufficient resources to allocate the request, the small cell schedules the transmission in the next superframe, and uses the beacon to notify the device accordingly. If there is no notification in the beacon (no resource available or the reservation request is denied), the device shall retransmit the grant request in the CAP with the **highest priority**. If an acknowledgment is required, the SC may reserve a dedicated slot for the acknowledgment in the CFP (DL).
- Contention-based access (insensitive data): in this case, the device transmits the packet during the CAP. If an acknowledgment is required, we assume that there exits independent

DL acknowledgement slots at the end of the CAP such that the SC transmits Ack packets without interrupting the UL data packets.

Exception report: Assuming this kind of traffic will be very infrequent; using the CAP in the superframe is a reasonable idea. ER transmission requires then the following operations:

- Device synchronises on the small cell beacon,
- Multiband CSMA-CA transmission on CAP period,
- All ER packets are supposed to be ACKed by the small cell.

Network commands: a key issue of DL for energy constrained devices is how to cope with device dormancy states and to make sure that the DL can be setup, having a system reactive enough to send a command within a minimum latency, if required. We propose to rely on an approach which is close to preamble-sampling MAC protocol for energy-efficient wireless sensor networks (WSN) like [17]. In this WSN protocol class, the devices sleep for most of the time, except during periodic short instants (T_{ch}) when they wake up and sense the channel. If the channel is sensed as idle, nodes are going back to sleep mode. If a device senses the channel as busy, it keeps listening until a packet is decoded. In preamble sampling protocols, all devices share the same channel sensing period but are not synchronized. Subsequently, a device which wants to communicate with another one has to use a wake-up preamble prior to the data payload, which must be at least as long as T_{ch}Refinements like the ability to learn the wake-up schedule of a device to reduce the duration of the preamble or the ability for a receiving device to notify the sender that it has awoken (i.e., the preamble is no longer useful) exist in the literature.

In the DL specification of our MAC protocol related to the transmission of network commands, we are reusing the preamble sampling concept that puts the burden of a packet transmission on the emitter, allowing the receiving mode to manage its power consumption by means of period channel checks (see below). An important input for specifying this check interval is the expected reactivity of the system: what is the maximum latency for a node to receive NC? This maximum latency depends on the application and may range from 1s to 10 min. In order to meet the maximum latency requirement, each IoT device (able to receive network commands) has to be configured so that it wakes up periodically for a short period, synchronizes on the beacon and checks whether a NC is pending. For each node, this wake-up period, called T_{w} in our protocol, is set to the maximum tolerable latency that comes with application requirement.

Basic mode: Assume SC has a network command for Device $\#i$ which has a wake-up period of T_w. The SC will include in the beacon the field that indicates that a NC is pending for device #i and this notification will be repeated in a number of beacons such as it covers a duration as long as T_w. The notification includes a timer (countdown) telling when the NC is actually emitted in the future (as shown in Figure 14). The device wakes up when the timer reaches zero to resynchronize to the beacon and to receive the NC. If the NC asks for a response, resource in the next superframe can be scheduled and indicated in the NC notification or the NC itself.

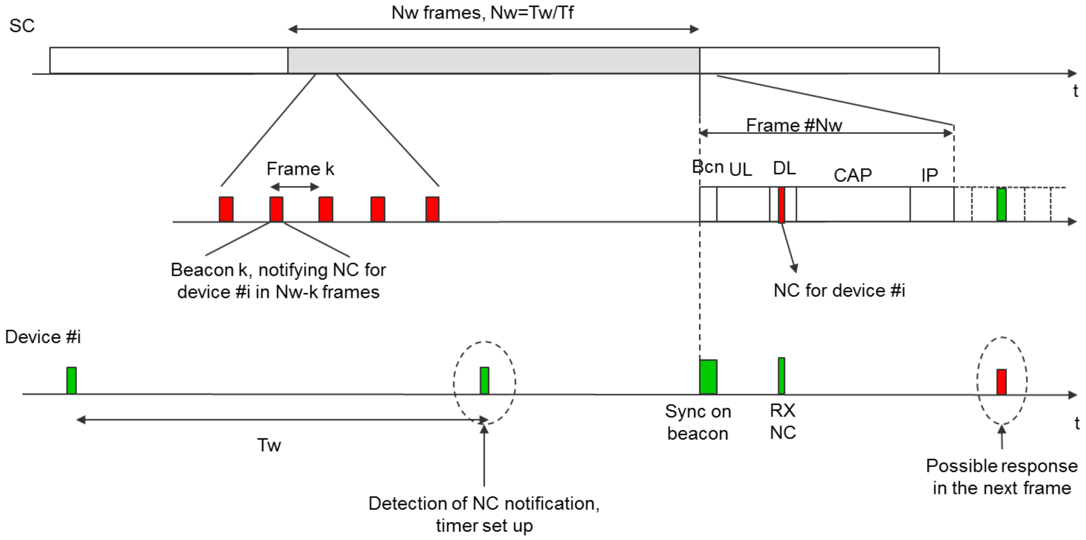

Figure 14: Basic mode for NC notification

NC refinement 1: wake-up acknowledgment: The basic mode consists in repeating the NC notification in the beacon over a period of time longer than the device wake-up period. On average, half of these repetitions are useless since the intended device will be awake. As in [18], the device can interrupt the NC repetition sequence by sending an ACK message in the CAP following the beacon which he manages to synchronise on. Thanks to this ACK message, the device triggers the emission of the NC in the following frame (Figure 15).

NC refinement 2: As in [19], SC can learn the device's wake-up schedule. Accordingly, the SC can reduce the duration of the preamble, to start the preamble emission just before the device wake-up instant. A margin has to be applied, taking into account the possible clock drift since the last time the device woke up (T_θ). This mode requires that devices have to inform (piggyback with an ACK or a response) the SC about their up-to-date wake-up schedules. If the SC does not have a recent wake-up schedule update (T_θ>T_w), the basic mode is used.

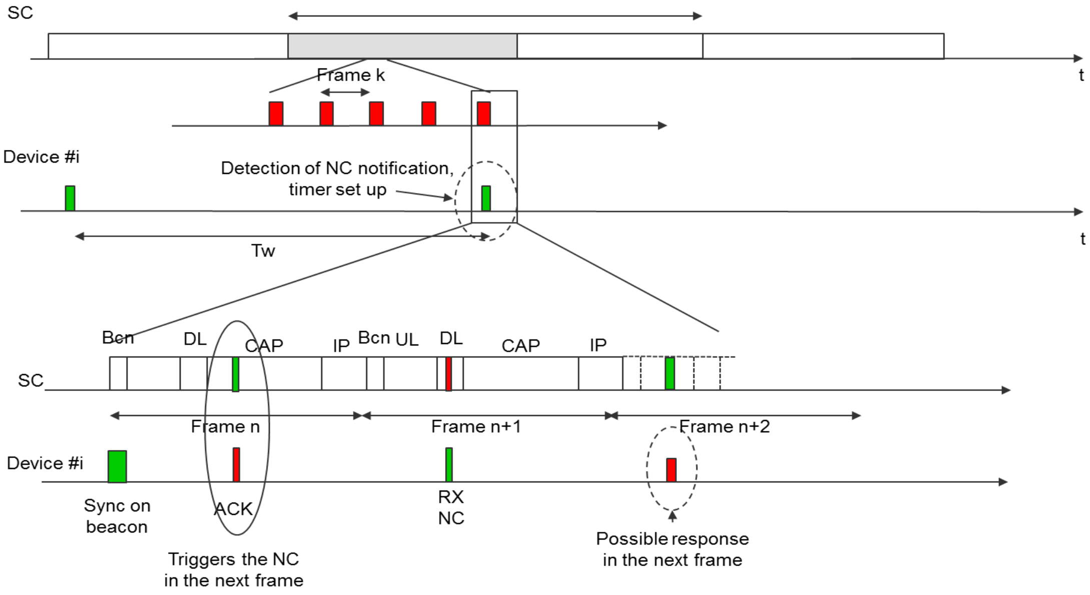

Figure 15: NC refinement 1: wake-up acknowledgment

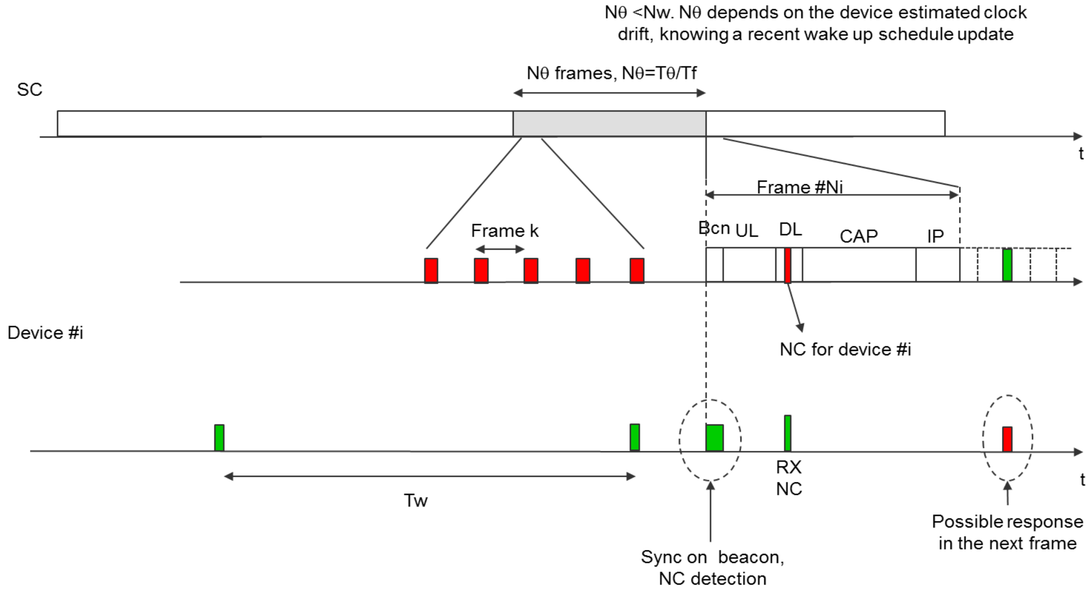

Figure 16: NC refinement 2

MAC parameters - Table 11 lists the value for the MAC sub-layer parameters.

Table 11: IoT MAC parameters

MAC parameters	value
mSuperframeDuration	614.4 ms
mMASDuration	1.2 ms
mMASCount	512
mBeaconSlotDuration	1.2 ms (1MAS)
mMaxFramePayloadSize	0 bits – 1600 bits (0 bytes- 200 bytes)
CWmin	16
CWmax	1024
SIFS	10 μs
DIFS	SIFS + 2SlotTime
SlotTime	*40* μs

The medium access slot duration of 1.2 ms has been considered in the superframe in order to support different packet sizes while respecting the duty cycle of each device (< 1%). It is worth noting that the total packet size is made up of payload size and header overhead of 20 bytes. Therefore, the time required to transmit the smallest packet size of 20 bytes using MCS 1 is 1 ms which falls within one slot. On the other hand, the corresponding time to transmit a packet payload size of 100 Bytes is 5.5 ms and 1.15 ms using MCS1 and MCS7, respectively. These times correspond to 5 slots and 1 slot, respectively.

4.1.3.3.3 Control channels / frames

The supported control frames for IoT MAC design are Beacon, ACK and RREQ frames. The **beacon frame** should include all the information for network operation:

- Reservation resource for uplink traffic,
- Reservation resource for downlink traffic,
- Frame structure
- Delimitation of the contention access period.

The beacon frame should also specify the mode used to send network commands as it will be later described. The information element IE (CFP IE and CAP IE) are considered to describe the resource reserved for each scheduled device within CFP and the resource retained for CAP. CFP IE is used to announce the reserved MASs and their corresponding bands. Meanwhile, CAP IE identifies the MASs in which contention access transmissions are allowed.

Beacon payload describes the current superframe. More specifically, it includes all information about CFP schedules, and CAP as presented in Table 12. Information elements (IE) for CFP-UP include owner device, target device, and scheduled resource (sub-channel, start of the slot and number of slots). IEs for CFP-DL include in addition to these fields a countdown timer field to indicate the time of sending the NC. CAP information element shall identify the contention access transmissions and shall include the start of the period and its length in number of slots.

Table 12: Beacon payload structure

CFP_UP IE field	CFP_DL IE field	CAP IE field
Owner device Target device Allocated resource: - Sub-channel - Slot start - Number of slots	Owner device Target device Allocated resource: - Sub-channel - Slot start - Number of slots Countdown timer (N_w)	Slot start Number of slots

The SC shall send **ACK frame** in broadcast manner for all devices waiting for an acknowledgement. The last two slots at the end of the CAP are reserved to send back ACK frame for all devices having send data frames in the CAP. For data frames sent in CFP UP, the last slot in CFP DL shall be reserved for the acknowledgment. ACK frame payload shall include the address of device waiting an ACK and the corresponding sequence number of data frame.

RREQ frame payload shall include the resource requested by the device for sending data. The resource request shall specify the length of data to be send and the priority of this request and optionally the acknowledgment mode (ACK or no ACK required).

4.1.3.3.4 Resource access (RACH design)

In the proposed MAC design for mIoT device operating in 868 MHZ band, contention access period is used for random access. More specifically, no dedicated resources are allocated for random channel access. The beacon in current superframe specifies the CAP delimiters. After receiving the beacon, a device that has data to send contents in the CAP uses the random access procedure described later in the section in order to get a channel access and send data.

4.1.3.3.5 Heterogeneous Resource Aggregation

Carrier activation as an unlicensed carrier shall be supported in this MAC design. In this particular MAC design, carrier aggregation (continuous and not contiguous) is not seen as a capacity extension feature but more on a multi-service connectivity, mixing mIoT applications, which does not require a high data rate. The IoT applications targeted here are more related to low-end IoT for which unlicensed spectrum is fairly convenient as they are generally delay tolerant with small to moderate packet payload size (20-200 Bytes).

4.1.3.3.6 MAC procedures

The MAC layer can perform the following procedures:

- Random Access Procedure
- Scheduled or contention based UL-SCH Data Transfer
- Scheduled DL-SCH Data transfer

Random Access procedure

The random access procedure is performed in the CAP and shall be triggered each time a device in the network has data to be send to the SC. This random access procedure is based on multi-channel CSMA/CA algorithm in order to enable the stations to contend with each other for channel access both in time and frequency domains. It uses simple techniques of medium sensing and deferring to avoid collisions. Figure 17 illustrates the functionality of proposed multi-channel CSMA/CA algorithm. It shall be performed as follows:

- Perform channel sensing to find the set of idle sub-channels.
- If all sub-channels are found to be busy, defer access for an expected busy duration. Otherwise, select randomly a sub-channel from the set of idle sub-channels.
- Generate a random backoff time (B) before transmitting in order to minimize the probability of collision. The backoff time is uniformly chosen in the range of $[0,W-1]$ for a contention window size W.
- Perform CCA for DIFS period. If the channel is sensed idle, perform backoff procedure. Perform CCA at each backoff slot duration, and decrement the backoff if the channel still idle. Otherwise, freeze backoff and differ access until the channel become idle again.
- When the backoff counter reaches zero, transmit the packet.

Before performing the random access procedure, the device shall initialize the following variables for each transmission attempt: NB and NA. NB is the number of times the backoff counter is frozen when the channel is sensed busy. NA is the number of random access attempts, corresponding to the number of times the device tries to get a random access to the medium.

The MAC sublayer shall also ensure that the backoff procedure and packet transmission can be complete before the end of the CAP. Otherwise, the device shall wait the start of the CAP in the next superframe to perform random access procedure.

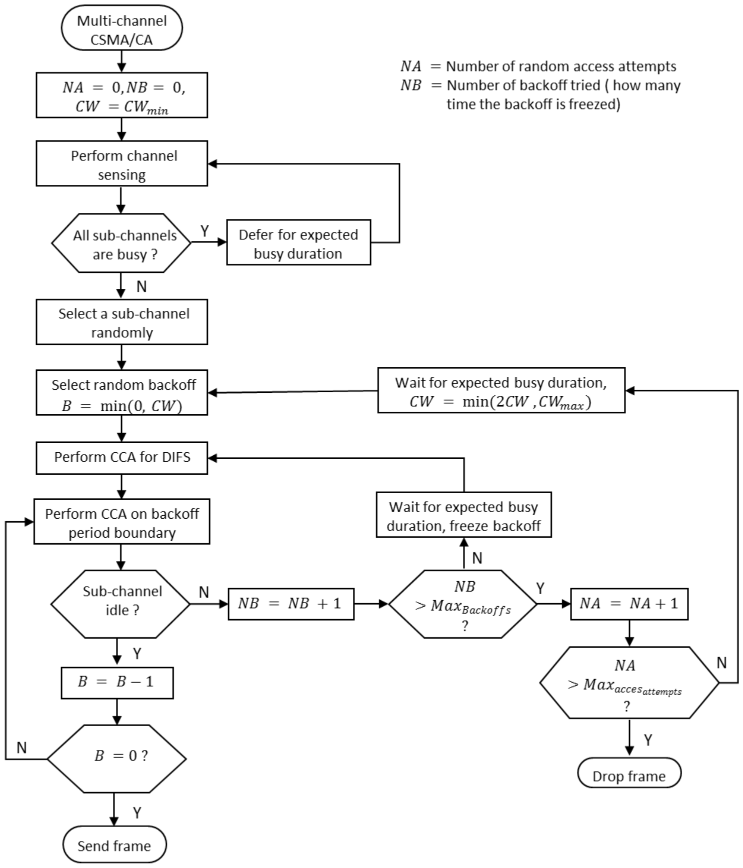

Figure 17: Random access procedure based on multi-channel CSMA/CA.

Scheduled and contention based UL-SCH data transfer

UL data transfer may be either done directly in the CAP (contention) or in the CFP (scheduled) based on previous negotiation.

Figure 18 illustrates the uplink data transfer procedure in the CAP. The device after synchronizing on the beacon shall perform a random access procedure in the CAP. After successful access to the channel, the device sends the data frame to the SC. If no acknowledgment is requested, the device shall assume that the transmission of the frame was successful and send a successful confirmation to upper layer. If an acknowledgment is requested, the device shall wait for an ACK before repeating the process of transmission, up to a maximum number of retries. Due to the imperfect nature of the radio medium, a transmitted frame does not always reach its intended destination. There are three different transmission scenarios:

<u>Successful data transmission</u>: The SC receives data frame and sends acknowledgment back to the device at the end of the CAP. The device receives the ACK. The data transfer is now successfully completed and a success confirmation shall be delivered to next higher layer.

<u>Lost data frame</u>: The SC in this case does not receive data frame, so no acknowledgment is sent back to the device. At the end of the CAP, if no acknowledgment is received, the device shall resynchronize with the next beacon, content to get access again in the CAP and retransmit the data frame. This procedure may be repeated up to a maximum number of retries.

<u>Lost acknowledgment frame</u>: contrary to previous case, the SC receives the data frame and send an acknowledgement back. However, at the end of the CAP, the device does not receive the acknowledgment frame. The device may retransmit the data frame up to a maximum number of retries.

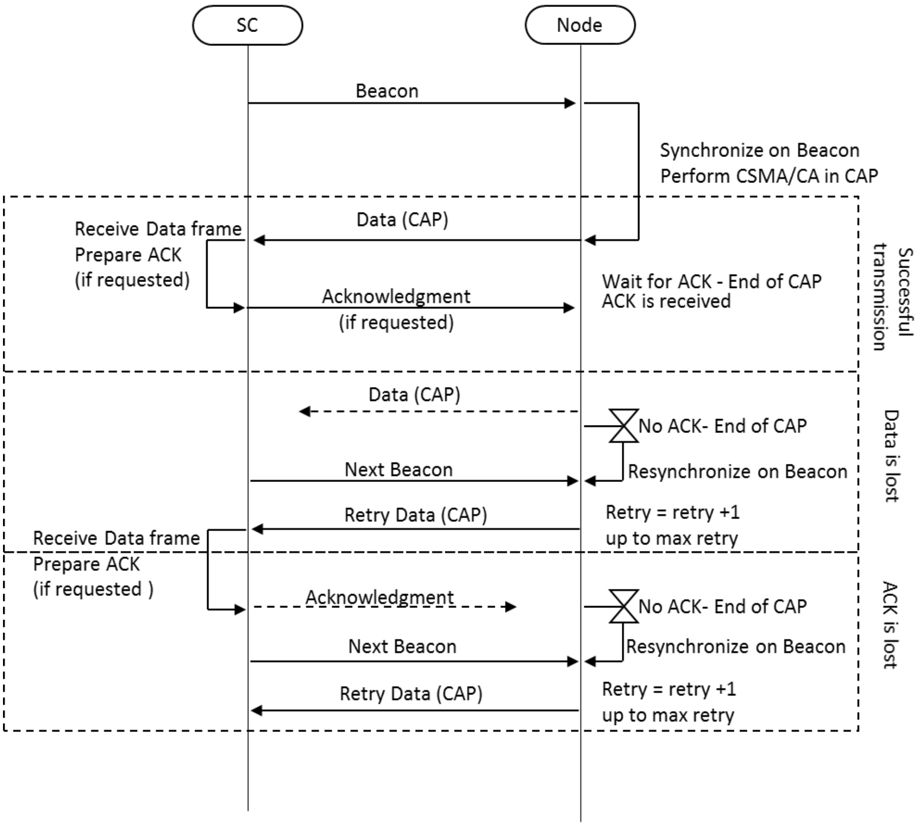

Figure 18: Procedure of UP data transfer in the CAP.

The procedure for **uplink scheduled transmission in CFP** is depicted in Figure *19*. In this period, a scheduled resource is allocated for the device by sending RREQ. The device after synchronizing on the beacon shall send a RREQ in the CAP following the random access procedure and shall specify the priority of this request. The default priority is set to zero. The SC upon receiving the RREQ decides whether to allocate a resource depending on the current available resource in the superframe, on the requested resource and on the priority of the request.

The SC shall be able to manage all the RREQ received. For this purpose, the SC shall maintain a table of available resource at the beginning of each superframe and shall store all the information of scheduled resource including the device address, the allocated resource (sub-channel, stating slot, number of slots), and the priority of the request. When receiving a RREQ, the SC shall check the available resource table. If more than one resources are available, the SC randomly select one, update the resource table, and the scheduled table. Otherwise, the SC checks the scheduled table. If the priority of the RREQ is higher than the priority of a scheduled table entry, the SC replaces this table entry. Otherwise, the SC drops the RREQ. The SC shall include all the CFP schedules in the next beacon, using the CFP_UL IEs.

The device after resynchronizing on the beacon, checks the CFP information element in the beacon. If uplink resource has been allocated, the device transmits the data in this allocated resource. Otherwise, the device shall retransmit the RREQ in the CAP again with higher priority using the random access procedure. If an acknowledgment is requested, the SC sends the acknowledgment at the end of CFP DL. In addition to previous transmission scenarios that can be produced (successful transmission, Data lost, ACK lost), the following scenarios shall be envisaged:

RREQ Lost: if the SC does not receive the RREQ, no allocated resource will be indicated in the next beacon. The device retransmits the RREQ by updating the level of priority.

Beacon lost (with CFP schedules): In this case, the SC receives the RREQ and indicates the scheduled resources in the beacon. However, the device lost the beacon and therefore, it shall wait next beacon and resend the RREQ in the CAP.

If data is lost or ACK is lost, the device shall retransmit the RREQ again up to a maximum number of retries. After maximum retries, the device shall drop the RREQ and the corresponding data frame and notify the upper MAC layer about this transmission failure.

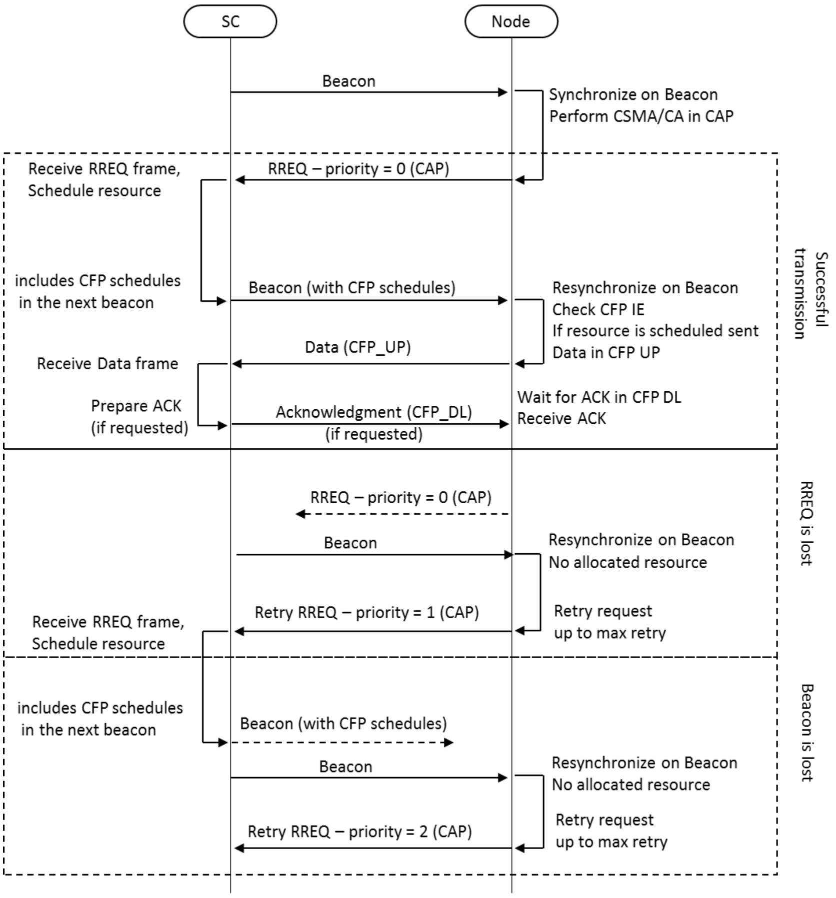

Figure 19: Procedure of UP data transfer in the CFP.

DL-SCH data transfer

Downlink data transfer in IoT MAC design is related to the transmission of network commands. The procedure of DL data transfer using basic mode is illustrated in Figure *20*.

The SC shall repeat the notification of NC in the beacon for the duration that covers the wake-up period of the device, as explained in section 4.1.3.3. When the device wakes up, it shall synchronize on the beacon, check the notification and the corresponding countdown timer that indicates at which time the NC will be send. When the countdown timer reaches zero, the SC sends the NC. If a response to the NC is requested, the device shall prepare the response, resynchronize on the next beacon and send the response in the corresponding allocated resources in the CFP.

If the beacon is lost, or the network command is lost, the SC shall repeat NC notification again over the duration that covers the device wake-up period.

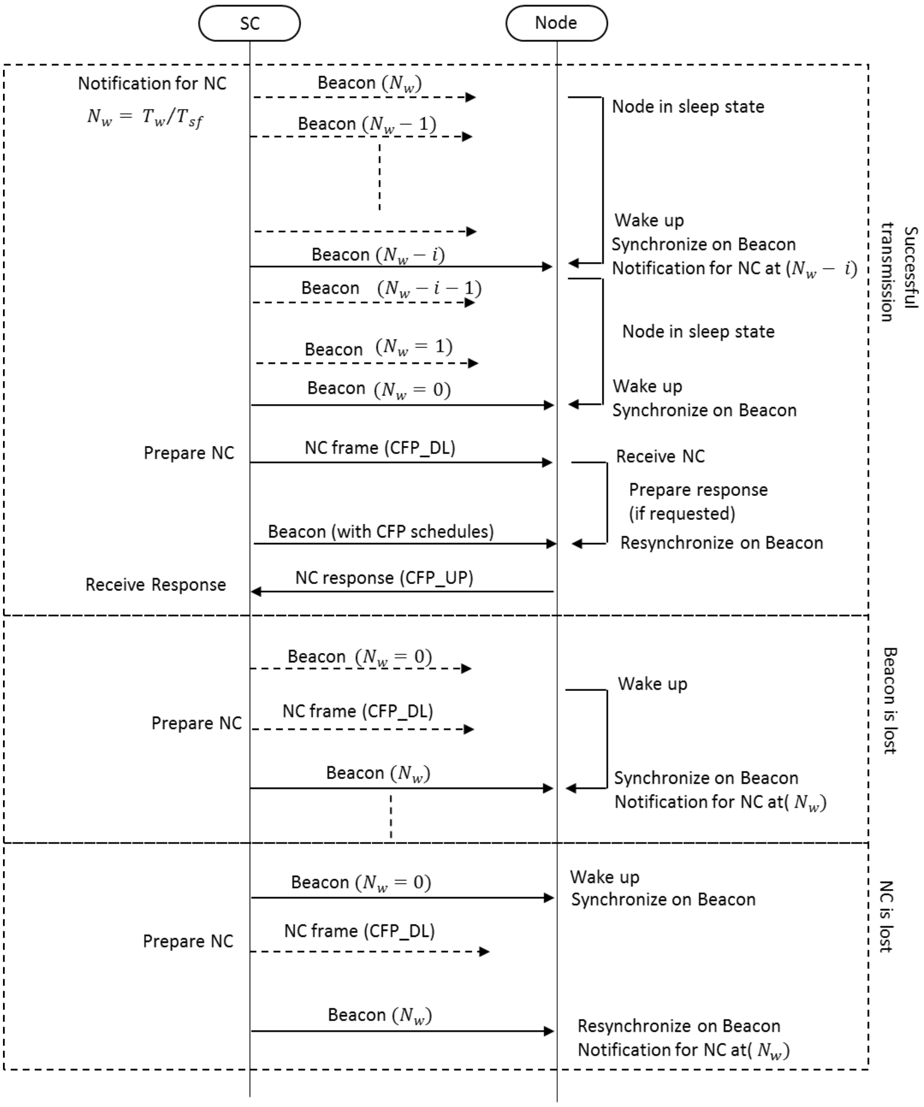

Figure 20: Procedure of DL transfer in the CFP.

PCH and BCH Receptions: PCH and BCH are not supported in MAC design for 868 MHz band.

4.1.4 MAC design #1b: MAC design for broadband traffic operation in the 5GHz band

This section deals with the design of a MAC protocol for the transmission of broadband traffic in the 5GHz band. This contribution describes how FBMC physical layer can be handled to offload some traffic on unlicensed spectrum. The way this traffic can be coordinated in some way with traffic sent on licensed resource is not part of this contribution. This is however a key item that should be addressed in the course of the project, so that an LAA-like access based on FBMC could be showcased. **A short discussion on the current regulatory framework and considerations affecting MAC design can be found in appendix 1.**

In addition to basic features the following new features have been integrated into the proposed MAC design:

- Possible support for carrier aggregation
- Enhanced QoS and spectrum utilisation

- Multi-RAT operation support
- xMBB support in unlicensed bands using UL and DL resource allocation

Unless specified in the text below, this MAC design is described for an autonomous operation in the 5GHz, close to Wifi or MuLTEfire[4], where no primary carrier in the licensed spectrum domain is used (i.e. licensed anchor) nor needed. In this case, all the data, control and monitoring planes are fully handled in the 5GHz band using control frame and data frames. It can however be used in an extended LAA manner, having a primary carrier which deals with the control plane; in this case the control frames defined below may be slightly different.

4.1.4.1 MAC Services

4.1.4.1.1 Services provided to upper layers

In addition to services already supported in [20] a number of new services (in Bold) are provided by the extented MAC design to upper layers :

- downlink data transfer
- **asynchronous uplink data transfer**
- radio resource allocation

4.1.4.1.2 Services expected from physical layer

The physical layer services provided to the MAC sublayer are mostly as identified in [20], but also new services (in Bold):

- **Multichannel uplink and downlink transmission**
- Frame transmission for both normal and burst modes;
- Frame reception for both normal and burst modes;
- Signalling of HARQ feedback
- **Measurements reporting** (e.g. Channel Quality Indication (CQI)).
- Header error indication for PHY and MAC header;
- Clear channel assessment for estimation of medium activity.

4.1.4.2 MAC functions

In addition to functions identified in [20], a number of new functions (in Bold) are supported by the extended MAC design:

- mapping between logical channels and transport channels;
- **multiplexing of MAC SDUs from one or different logical channels onto transport blocks (TB) to be delivered to the physical layer on transport channels;**
- **demultiplexing of MAC SDUs from one or different logical channels from transport blocks (TB) delivered from the physical layer on transport channels;**
- scheduling information reporting;
- error correction through HARQ;
- priority handling between UEs by means of dynamic scheduling;
- priority handling between logical channels of one MAC entity;
- Logical Channel prioritisation;
- transport format selection;
- radio resource selection.

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[4] http://www.multefire.org/

The location of all functions and their relevance for uplink and downlink respectively is illustrated in Table 13 (new functions are highlighted in Bold)

Table 13: MAC function location and direction association for design #1b

MAC function	UE	eNB	Downlink	Uplink
Mapping between logical channels and transport channels	X		X	X
		X	X	X
Multiplexing	X			X
		X	X	
Demultiplexing	X		X	
		X		X
Error correction through HARQ	X		X	X
		X	X	X
Transport Format Selection		X	X	X
	X	X		
Priority handling between UEs		X	X	X
Priority handling between logical channels of one MAC entity		X	X	X
Logical Channel prioritisation	X			X
Scheduling information reporting	X			X
Radio Resource Selection	X			

4.1.4.3 Protocol Details

This section provides information on the proposed MAC protocol design and operation.

4.1.4.3.1 Frame Design and Structure

The baseline of the frame structure relies on the ECMA 392 standard [20], which is very close from the IEEE 1900.7 standard, and therefore from the MAC frame we developed for the IoT case. This is a beacon-enabled frame, composed of slots that could be allocated to uplink or downlink communications, depending on the load in the network. The decision of the number of slots allocated to uplink and downlink is made by the scheduler, according to the traffic load. This is beyond the scope of this work and we assume a PF scheduler.

From this standard, we keep the frame structure based on a beacon and time-slots (composed of 2 Medium Access Slots - MAS), the frame being composed of

- A scheduled access period with an uplink and a downlink part. The slots of each portion spans over the whole channel, meaning that the scheduler can allocate resource blocks (RBs) based on a number of slots on a number of sub-channels (subcarriers), depending on the traffic type and CQI. In the uplink part there is no need to synchronise the devices which transmit on adjacent channels since FBMC support this asynchronicity; a guard time in slots has to be provisioned so that there is no temporal leakage from one slot to the next one. The length of the scheduled period and the beacon is actually the “Channel Occupancy Time” (see Figure 88 in Annex 1). .
- A contention access period located at the end of the frame and composed of a reduced number of slots. The CAP is optional and shall be activated in the case there is no licensed carrier to use as a primary carrier. In this case, the CAP is used to let UEs transmit association/dis-association packets, ACK, CQI updates, UL/DL grant requests and acknowledgments of “paging” requests sent by the small cell.

- A SC broadcasted ACK frame where uplink traffic, if any, are acknowledged, indicating, for all the active UEs with scheduled UL traffic ACK/NACK of the received packets and MCS update for the packets to come. This broadcasted ACK frame is transmitted on one slot
- An Idle period at the end of the frame. This is required by the European regulation which mandates that at least 5% of the frame length shall be idle. This period can be advantageously used by devices to sense the channel and feed the spectrum manager with sensing report accordingly.

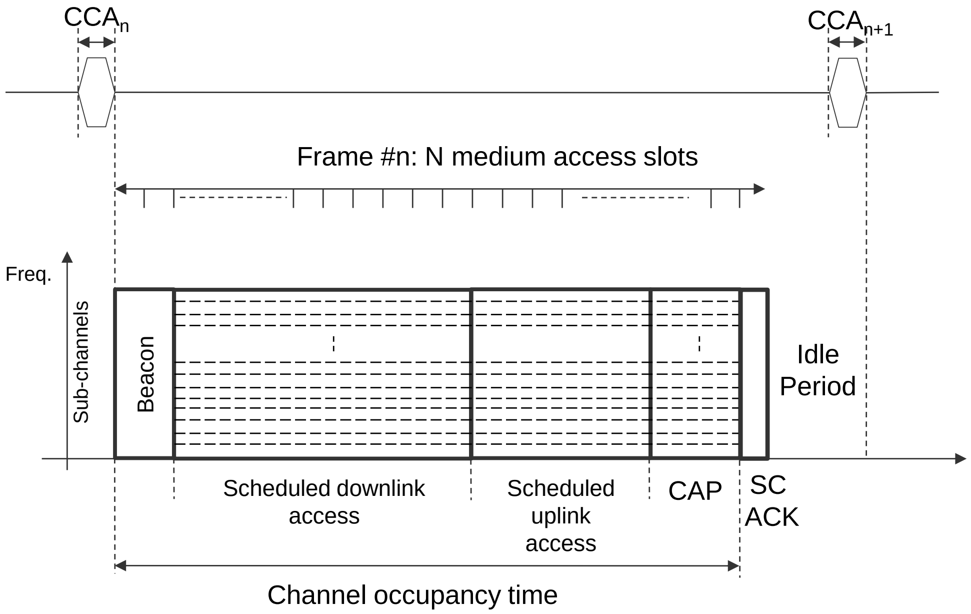


Figure 21: Proposed frame structure for broadband access in 5 GHz

Frame parameters are reported in Table 14.

Table 14: FBMC broadband access frame parameters

MAC parameters	value
mMASDuration	500 µs
mMASCount	Variable
mBeaconSlotDuration	1 ms (2MAS)
mMaxFramePayloadSize	Variable
CWmin	16
CWmax	1024
SIFS	10 us
DIFS	SIFS + 2SlotTime
Backoff Slot duration	40 µs

According to the regulation, the Fixed Frame length triggers the CCA period of the small cell. If the small cell gets an indication of a busy channel after a CCA, it shall not transmit a beacon during the next Fixed Frame Period. In the case of using the 5GHz band as a supplemental carrier, the CCA timing is advertised on the primary carrier operated in licensed spectrum. This would allow devices to manage the activation and de-activation of the 5GHz transceiver and therefore manage the power consumption. In the case the 5GHz is used with no licensed anchor, devices have to seek for beacons with no means to optimize their power consumption, except provisioning the possibility of relying on DRX if it turns out that a beacon is not received.

4.1.4.3.2 *Frame structure optimization*

Related to the block diagram depicted in section 3.1, this section gives an overview of how Higher MAC can modify the frame structure presented on Figure 21, according to the traffic load or interference conditions. This configuration is provided as a default configuration by the "Frame format adaptation" of the "coexistence coordination" entity which can further tune it, depending the experienced level if interference; as well "Frame format" of the "eDSA inter-RAT coordination" entity can also modify it depending on the load and traffic types (best effort vs. high QoS traffic). Optimizations may include

- Scheduled periods durations management so that the frame can be tuned to support a given traffic profile (mainly downlink vs. balanced traffic patterns). Alternatively, the CAP can be tuned using the priority list available (see section 4.1.3.3.3) to provide a better reliability to ACK and CQI updates when the number of active UEs with scheduled DL traffic is getting large.
- Fixed Frame Period reduction: if the channel is shared with other systems and the interference level is high, the RRM would reduce the Frame duration, implying to give CCA a dominant role.
- CCA duration extension: when coexisting with another system, the higher MAC may give more priority to it by extending the CCA duration. This extension also provides for richer sensing information to report to the spectrum manager.

4.1.4.3.3 *Multiple Access*

Multiple access in this design is based on OFDMA for both uplink and downlink channels, using the same concept of resource block of LTE systems. A resource block is therefore an allocation of 3 active subcarriers, spanning on 180 kHz, during a medium access slot. The scheduler is responsible of allocating uplink and downlink resource blocks to active logical channels, assuming the same kind of scheduler as those used in LTE. Interestingly, FBMC tolerates asynchronous transmission in adjacent channels if a guard band of one inter carrier spacing is introduced. This means that uplink resource allocation at small cell scheduler can be done quite straightforwardly. *Figure 22* depicts this multiple access scheme on the frame structure, for the scheduled access parts.

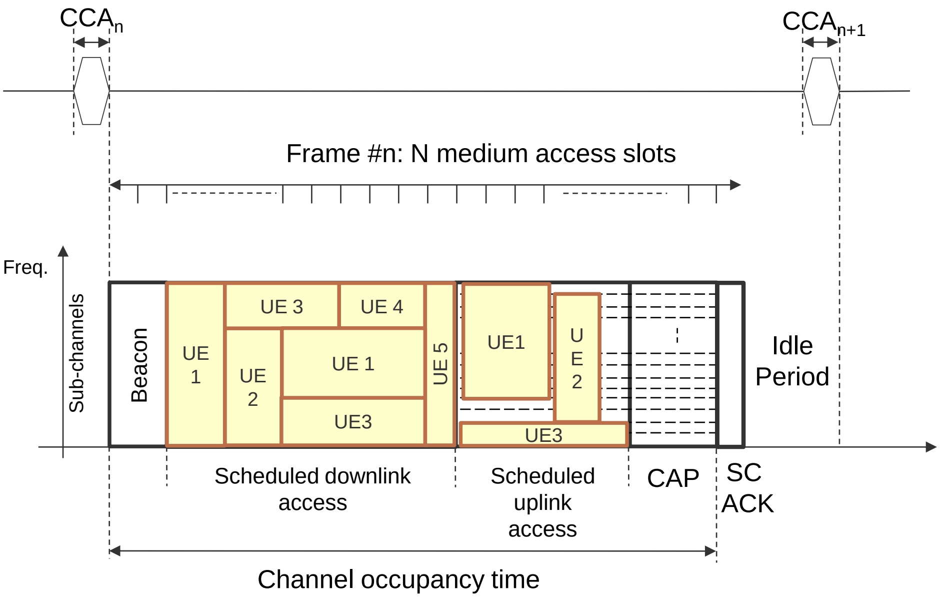


Figure 22: Multiple access scheme in FBMC broadband MAC

In this beacon-enabled frame structure, the beacon is initially used for cell identification and network synchronization and carries control information about the scheduled uplink and downlink access as well as the contention-based access as described in next section. In the scheduled downlink access, the SC sends the requested information data to the users based on user priority, QoS requirements and the availability of resources. The scheduled uplink access is used by users that have previously demand an UP grant access to send uplink data. If an active UE has a both scheduled uplink and uplink resources, control information (CQI, ACK) may be multiplexed with data in the scheduled part and not sent in the CAP as previously stated.

As far as contention access period is concerned, this period is used to initiate network access (association/de-association) and send ACK/NACK and CQI updates. In CAP, UEs perform a random access procedure based on multi-channel access, using an elementary channel of 18 active sub-carriers (6 resource blocks), meaning channel bandwidth of 1 MHz. Thus, 8 elementary channels and 16 elementary channels are assumed available for a system bandwidth of 10 MHz and 20 MHz, respectively. Since contention-based access is subject to collision, the time spent to get access to the medium may be long. The SC may in this case set the priority of traffic to be send in the CAP as described in the following sections. At the end of the CAP, the SC schedules one slot (2MAS) to send ACK/NACK for the scheduled uplink data.

4.1.4.3.4 Control Channels/Frames

Following the same way this is done for the previous MAC for IoT support in 868 MHz band, the control channels are contained in the control frames which are beacon frame, ACK and RREQ frame. The beacon payload will be then composed of information elements, like in section 4.1.3.3.3, which describe the frame organisation (UL and DL scheduled access and UP contention access, inactive period). Because this MAC can be used in a carrier aggregation mode corresponding to the "5G-AIV Scheduler of the lower-MAC (see Figure 2) and/or because the Higher MAC may adapt the LBT parameters to make the CCA period longer for instance or the contention access algorithms, specific additional information shall be included in the beacon in a dedicated Information element (FRAME_IE), compared to the IoT case. Table 15 shows the different IEs composing the beacon.

Table 15: Information elements in the beacon payload (design #1b)

FRAME IE field	CFP_UP IE field	CFP_DL IE field	CAP IE field
Owner device Carrier aggregation Frame length (slots) Bandwidth Inactive period - Start slot - Number of slots	Owner device Target device Allocated resource: - Frequency resource blocks - Slot start - Number of slots - MCS	Owner device Target device Pending/scheduled Allocated resource: - Sub-channel - Slot start - Number of slots - MCS ACK mode (CAP or CFP)	Slot start Number of slots Traffic priority

In the FRAME IE, the second field allows to indicate whether the frame is sent in conjunction of a primary carrier or not; when this flag is set to '1', this corresponds to an aggregation scheme which implies that the other IEs are void since all the control traffic is transmitted on the primary carrier. The other fields are straightforward indications of the frame length and parameters of the inactive period.

In the CFP_DL IE field, the "Pending/Scheduled" field is a flag which intends to indicate whether the SC has pending data for the device which will be scheduled if the device sends an acknowledgement (flag value: '0'); in this case, all the fields but the device address are void. If the flag is '1', this means that the data are scheduled in the CFP of the frame, according to the description of the other IE fields.

In the CAP IE fields, the “Traffic priority” is a descriptor of the CAP organization, which will be explained in section 4.1.4.4

ACK/NACK frames are sent by UEs of the data received within the scheduled DL part of the frame. Together with the acknowledgment, the UE sends the CQI (SINR) calculated on the resource blocks that has been allocated, so that the SC can update the MCS accordingly in the next frame. ACK/NACK frames are sent either during the CAP or during the scheduled UL data for UEs having both DL and UL scheduled traffic. Typical fields of ACK frames are owner and target devices, sequence numbers of data fragments successfully received, sequence numbers of data fragments received in failure and CQI per resource blocks.

RREQ frame payload shall include the resource requested by the device for sending data. The resource request shall specify the traffic direction (up- or downlink), the traffic class (corresponding to a given level of QoS; traffic classes definition are out the scope of this document), the length of the data to be sent, the CQI per RB, which has been calculated by the device when receiving the beacon.

P_ACK frames are acknowledgment frames sent by devices which have a CFP_DL IE in the beacon with the “Pending/Scheduled” set to ‘0’. In this case, the device shall send, in the CAP a P_ACK frame to inform the Small Cell that it can proceed to the scheduling of the data in the next frame. The payload of this frame also includes the CQI per RB, which has been calculated by the device when receiving the beacon

4.1.4.3.5 Resource access (RACH design)

Like this is done in the IoT MAC design, contention access period is used for random access. More specifically, no dedicated resources are allocated for random channel access. The beacon in current superframe specifies the CAP delimiters. After receiving the beacon, a device that has data to send contents in the CAP uses the random access procedure described later in the section in order to get a channel access.

4.1.4.3.6 Carrier aggregation

This MAC design has been described as if it operates in a standalone mode in the 5GHz band, without being used as a secondary carrier in the licensed spectrum domain. However, it can fully support carrier aggregation like in LAA; in this case, it assumed that all the UL and DL control traffic will be transmitted on the control plane on the licensed carrier (grant request, HARQ control, CQI report and allocation resource designation). In this case, the beacon as it has been described is not useful anymore and is reduced to a simple synchronisation preamble, letting UEs identify the boundaries of the TTIs and retrieve the DL resource blocks they have to demodulate as well as locate the UL scheduled CFP whenever they have data to transmit in.

4.1.4.4 MAC procedures

The goal of this section ist to detail fundamental procedures for the channel access, dealing with random access, uplink and downlink scheduled data transmission.

Random access procedure is based on contention based multi-channel access in the CAP in the similar way that has been discussed for the proposed IoT MAC design. Multi-channel CSMA/CA algorithm is also considered by users to get a random access to the channel in both time and frequency domains, like in section 4.1.3.3.6.

This random access procedure is triggered in more additional cases as follows:

- When user has an uplink request for UP resources grant,
- When user has a downlink request for DL resources assignment,

- When user has no UP grant and need to send an ACK frames back to the SC for data received within the scheduled DL access,

Due to the variability of the traffic that must be supported in this period, prioritization is considered to get access in the medium. The SC may configure specific resources in the CAP to handle prioritization of traffic; this prioritization depends on traffic type, the number of the users as well as the scheduled uplink and downlink resources. The traffic priority in the CAP must be specified in the beacon in the CAP IE field. Three traffic priorities can be configured as follows:

- CAP traffic priority = 0: no prioritization, all resources can be accessed by all users at any times.
- CAP traffic priority = 1: the prioritization is set for sending ACK frames back to the SC. In this case, 75 % of resources are reserved for ACK frames and 25 % of resources are reserved for handling uplink and downlink reservation requests or management commands (association, etc.)
- CAP traffic priority = 2: contrary to the previous case, the priority is set for sending uplink/downlink requests and management commands. Assumption is made that 75 % of resources are reserved for requests and the remaining 25 % of resources for ACK frames.

Device initiated UL-SCH Data Transfer: UP data transfer is done in the scheduled uplink access similarly to the scheduled uplink transmission proposed for IoT MAC design. In this transmission mode, the UE after receiving the beacon, makes a random access procedure asking for UP grant in the CAP. The SC uses the beacon to notify the UE about the scheduled UP resource reserved to send the data. The only difference is in the acknowledgment procedure, the SC in this case reserve two slots at the end of the CAP for sending ACK frames back to the UE. This procedure for UP data transfer for the proposed broadband access is depicted in Figure 23 . If the SC is able to correctly decode the uplink information data, it sends back an ACK frame to the UE at the end of the CAP. Otherwise, the SC sends back a NACK frame including the corresponding MCS for next transmission. The SC may also in this case keep same UP resource or reallocate new UP resource to the UE. When receiving a NACK, the UE shall resynchronize to the beacon, checks uplink grant and resent uplink data up to a maximum number of retries.

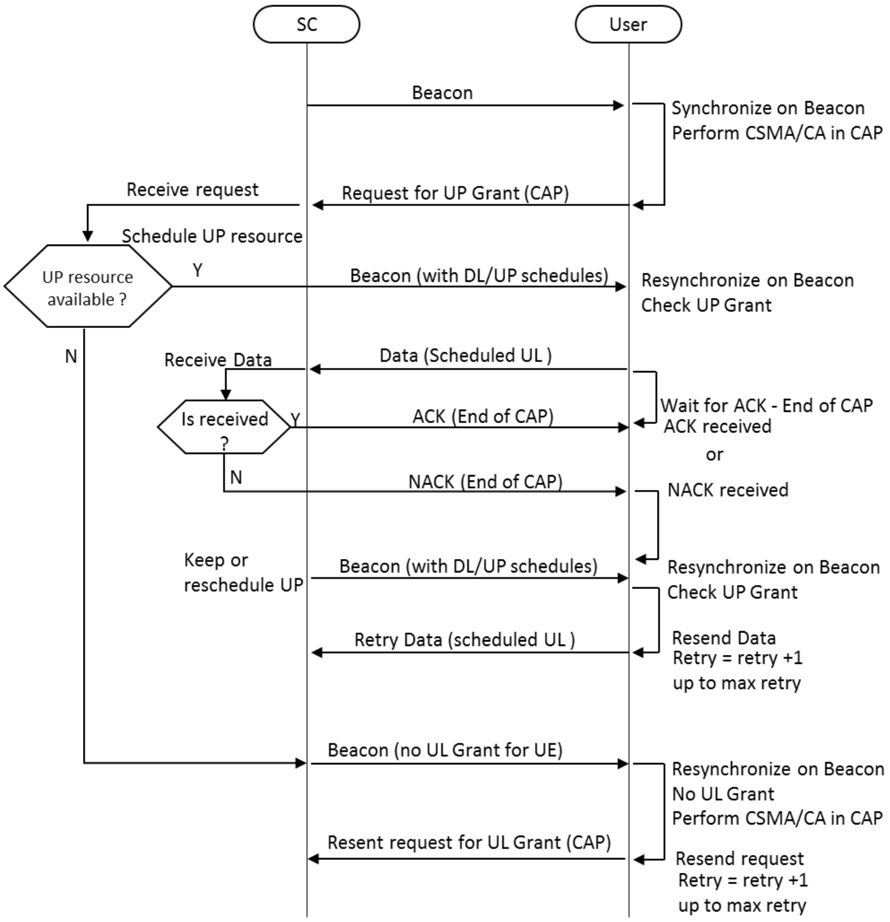


Figure 23: Procedure of scheduled UP data transfer (Design 1b)

Device initiated DL SCH Data Transfer: For broadband access, the downlink traffic is supposed to be the dominant traffic. In this scheduled downlink data transfer, the SC sends data information requested by the scheduled UEs currently connected to the SC. Figure 24 illustrates the procedure of scheduled downlink transmission initiated by the UE, which shall be performed as follows:

- The UE after synchronizing on the beacon sends a reservation request for assignment by including the CQI over the beacon.
- The SC, based on the UE priority, resource availability and channel quality, decides to schedule or not DL resource for the UE and includes this DL assignment (if any) in the next beacon. The SC may also decide to schedule uplink resource for sending back an ACK/NACK and CQI report.
- The UE after resynchronizing on the beacon, check for DL assignment, if any, the UE receives data information in the corresponding scheduled DL resource.
- If an UP grand is assigned to the UE to send data, the UE can multiplex the uplink data, the ACK/NACK and CQI reports and send them to the SC.
- If there is no uplink resource, the UE in this case shall perform a random access procedure in the CAP to send back the ACK/ NACK and CQI.
- If no DL resource is assigned to the UE, the UE shall resynchronize on the beacon and a random access procedure in the CAP to resent the request up to a maximum number of reties.

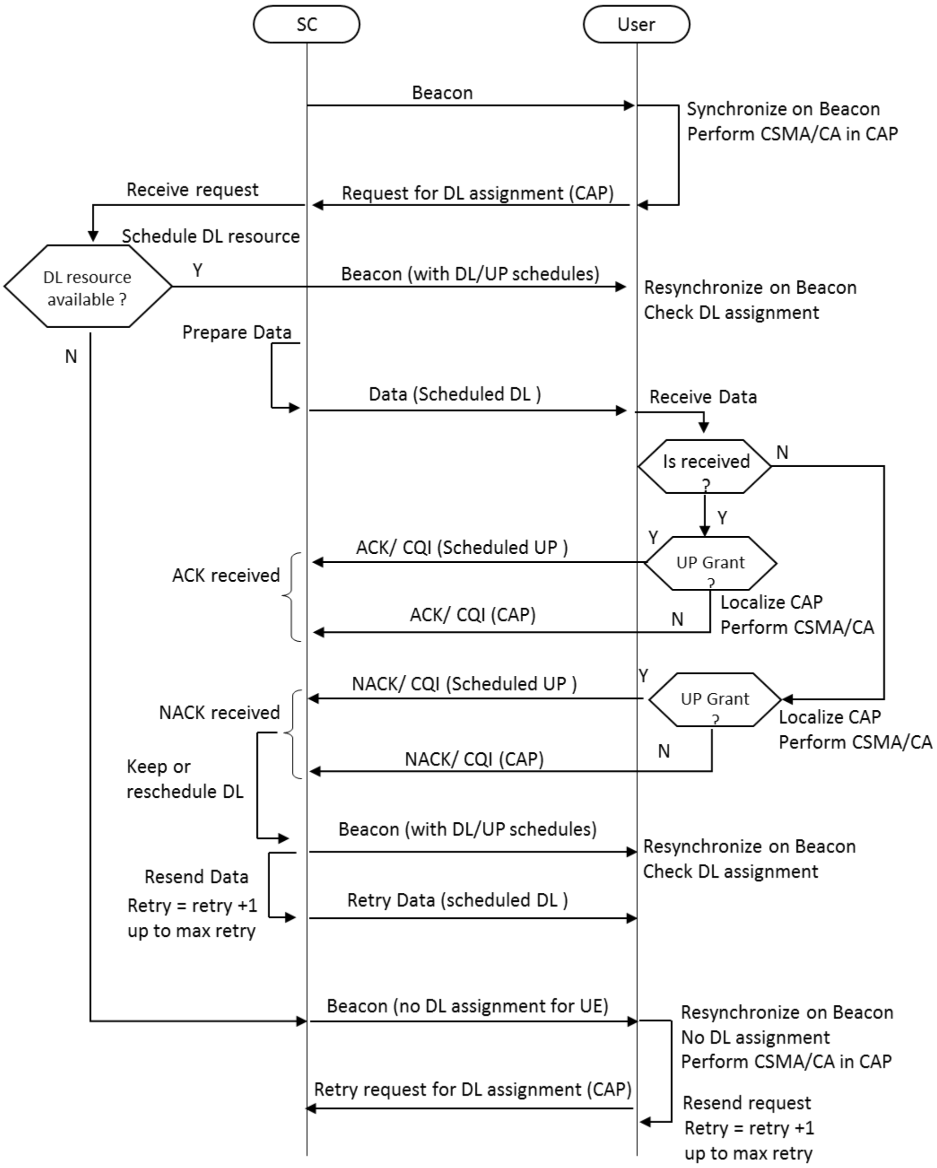


Figure 24: Procedure for scheduled DL data transfer (Broadband)

PCH Reception and BCH Reception: PCH and BCH receptions are not explicitly considered in the proposed broadband MAC design since these procedures are supported in the beacons, respectively by indicating possible pending data in a CFP_DL IE in the beacon and by receiving beacon.

However, Figure 25shows the procedure of paging a device for enabling a network initiated communication, by means of a CFP_DL IE with the “Pending/Scheduled” flag set accordingly (for further details, see section 4.1.4.3.4). The network-initiated communication shall be enabled when the SC has some data to be sent to the UE such as downlink data, warning information or system information update. It can described as follows:

- The SC includes a pending flag for the UE in CFP_DL IE in the beacon,
- Upon reception of the beacon, UEs shall check if there is any pending data. When decoding the “pending” CFP_DL IE, the destination UE shall perform a random access procedure to get access in the CAP and send back P_ACK or P_NACK frame by including the CQI over the beacon.
- If the SC receives a P_NACK frame, the SC repeats the pending notification in the next beacon. If a P_ACK is received, the SC shall schedule resource and included the corresponding DL schedules in the beacon.

- The UE shall resynchronize on the beacon and check for DL assignment to receive data. If data is correctly received and decoded, the UE shall perform a random access procedure in the CAP and send back an ACK including the CQI over the scheduled DL resource, the transmission is therefore successful.
- If the SC receives a NACK frame, the SC shall perform a retransmission procedure.

We note also that an uplink transmission can be also initiated by the SC when the SC required some data from the UE. Similar procedure can be performed by including a CFP_UP IE with Pending/Scheduled flag instead of CFP_DL IE.

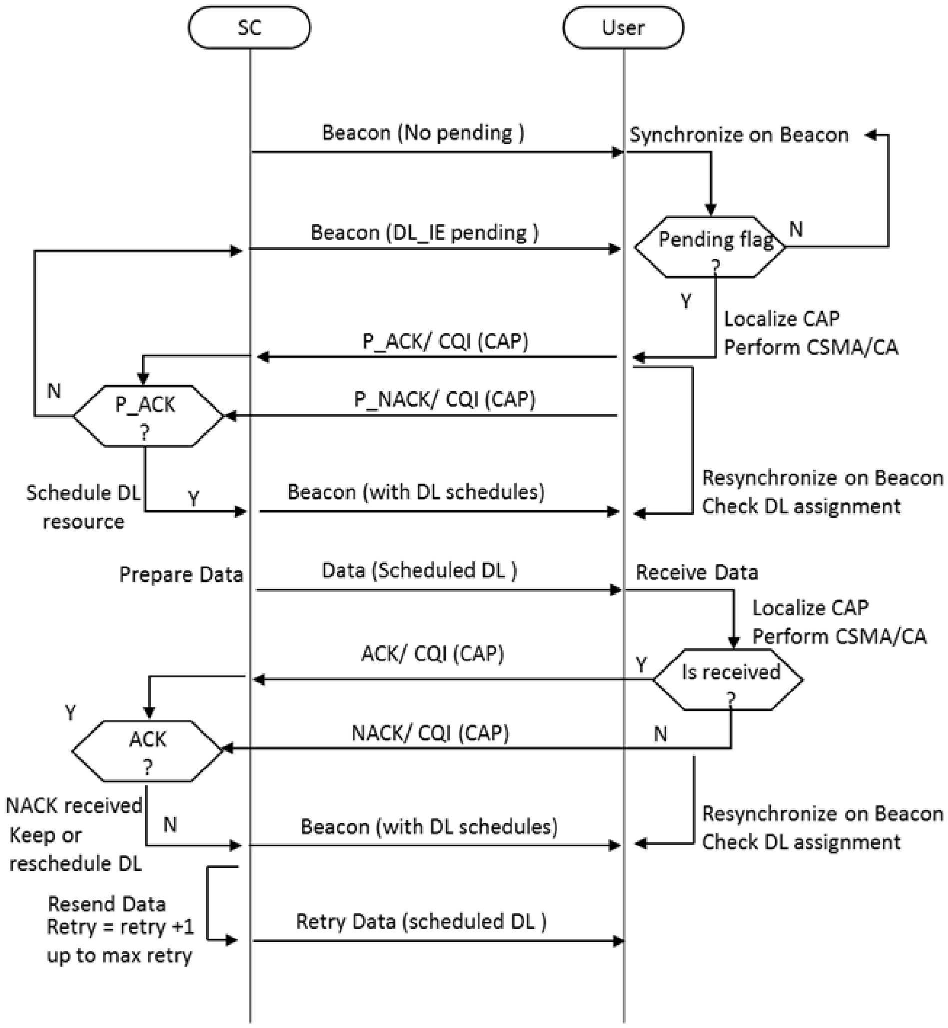


Figure 25: SC-initiated scheduled transmission of DL traffic.

4.1.5 New Features in MAC design #1

4.1.5.1 Support of different classes of QoS in massive IoT

As previously mentioned, IoT is composed of many traffic patterns which will be mainly dominated by uplink traffic including either periodic reports of non sensitive data which don't require any acknowledgment upon reception or alert type communications which in turn require a high packet delivery probability and acknowledgment. Even if most of the traffic is uplink, downlink communication is however an important part since some IoT are actuators which may be triggered by network commands which may expect low latency responses (of the order of seconds). Using a MAC frame configuration composed of parts tailored for uplink and downlink access, using either a contention or scheduled access modes, the different procedures of medium access for the different traffic types allow to accommodate these different requirements. In addition, the MAC design takes advantages of the flexibility of FBMC for uplink traffic, relying on multi-channel access which allow to support very high number of IoT devices per small cells.

Also, when dealing with IoT, energy efficiency is a critical requirements since most of the devices will be battery powered and are expected to have a lifetime up to ten years in some applications like smart metering. The MAC protocol presented before is built on a beacon-enabled frame which accommodate duty-cycled activity of devices, according to their traffic pattern (up or downlink) and generation rate. Uplink traffic transmission only requires lightweight medium access procedure after a straightforward beacon synchronisation. Thanks to duty-cycling the node reception, the downlink traffic transmission scheme of the MAC design meets the requirement of energy efficiency by means of advertising network commands process, while ensuring an almost bounded latency.

4.1.5.2 Stand alone or spectrum aggregation support

Being probably more relevant for its broadband version on 5 GHz band than for the IoT one, this MAC design can address a genuine stand alone operation mode with no anchor carrier in licensed spectrum, like MuLTEfire does. In this case, the MAC design is a very promising solution for high QoS broadband traffic either being device- or network initiated. Although being operated in unlicensed spectrum (being straightforwarly transposable in licensed and lightly-license spectrum, though) the frame structure is tailored for non contention access where time-frequency resource can be allocated to UEs depending on their QoS requirements. FBMC modulation characteristics are exploited for both facilitating the uplink transmission where the asynchronicity of UEs is natively supported and for maximising the spectrum efficiency by reducing the required guard bands between physical resource block allocation and adjacent carriers.

Whereas standalone operation is enabled by relying on uplink and downlink control packets (beacon, RREQ, P_ACK, ACK), this MAC design can be used in a carrier aggregation with a primary carrier, which may cconvey all the control traffic. In this case, the beacon-enabled transmission scheme can be turned off, mostly reducing the beacon to a synchronisation preamble and a lightweight broadcast payload.

4.1.5.3 Dynamic frame configuration

Compliant with the eDSA concept where inter-RAT coordination and coexistence coordination entities of the higher-MAC layer are able to tune the MAC frame format to adapt it to varying SINR or varying traffic requirements, this MAC design is built on flexible frame structure. Whether it be for IoT or broadband versions of this design, the size of uplink and downlink parts can be adapted and uplink traffic can be balanced between contention and non contention access schemes. The broadband MAC design even allow to reserve frequency resource of the contention access period for traffic control frames (ACK/NACK, P_ACK) against network management signalling, depending on the number of active devices. Given the beacon-enabled operation, the modification of the frame structure can be modified without further notice to UEs by changing the frame information element in the beacon payload.

Along the same idea, both IoT and broadband versions of the MAC protocol are able to be tuned in such away that coexistence with neighbouring systems can be facilitated. Indeed, an inactive period is provisioned and made tunable to share the access to the shared band in a fair manner, like in the Almost Blank Subframes or CSAT techniques in the context of LTE. In the data transmission period of the frame, coexistence can be favorised by selecting contention access procedure where the access can be gained after a number of clear channel assessments.

4.2 MAC Design #2: Broadband wireless access in dense hetnets

This section describes the required DL and UL MAC functionalities in order to support broadband wireless access in dense heterogeneous network (HetNet) scenarios.

The main goal of this MAC design is to support as much traffic as possible with a defined QoS. Nowadays, commercial networks experiment a constant increase of its spectrum demand and, for that reason, one of the main goals of 5G is to support 1000 times more traffic relative to current values. In order to treat with this challenge, SPEED-5G project proposes the use of the eDSA techniques which efficiently uses the available spectrum bands considering licensed, lightly licensed, and unlicensed bands. The use of these bands is done depending on, for instance, the traffic type, the UE characteristics or the instantaneous spectrum usage. Since the channel characteristics are non-static, the proposed MAC layer is ready to be (re)configured in real time for an optimal spectrum band usage.

In addition to basic features (as outlined in section 4.2.4) the following new features have been integrated into the proposed MAC design:

- Multi-RAT and multi-channel operation
- Semi-static IoT scheduling support
- Configurable control data region
- Control data period with DRX
- 3D Scheduling support

4.2.1 Relation to the MAC Framework

The mapping of the MAC design described in this section related to the SPEED-5G MAC framework (of figure 2), is depicted in Figure 26, highlighting the considered impacted functions by means of colouring them in black.

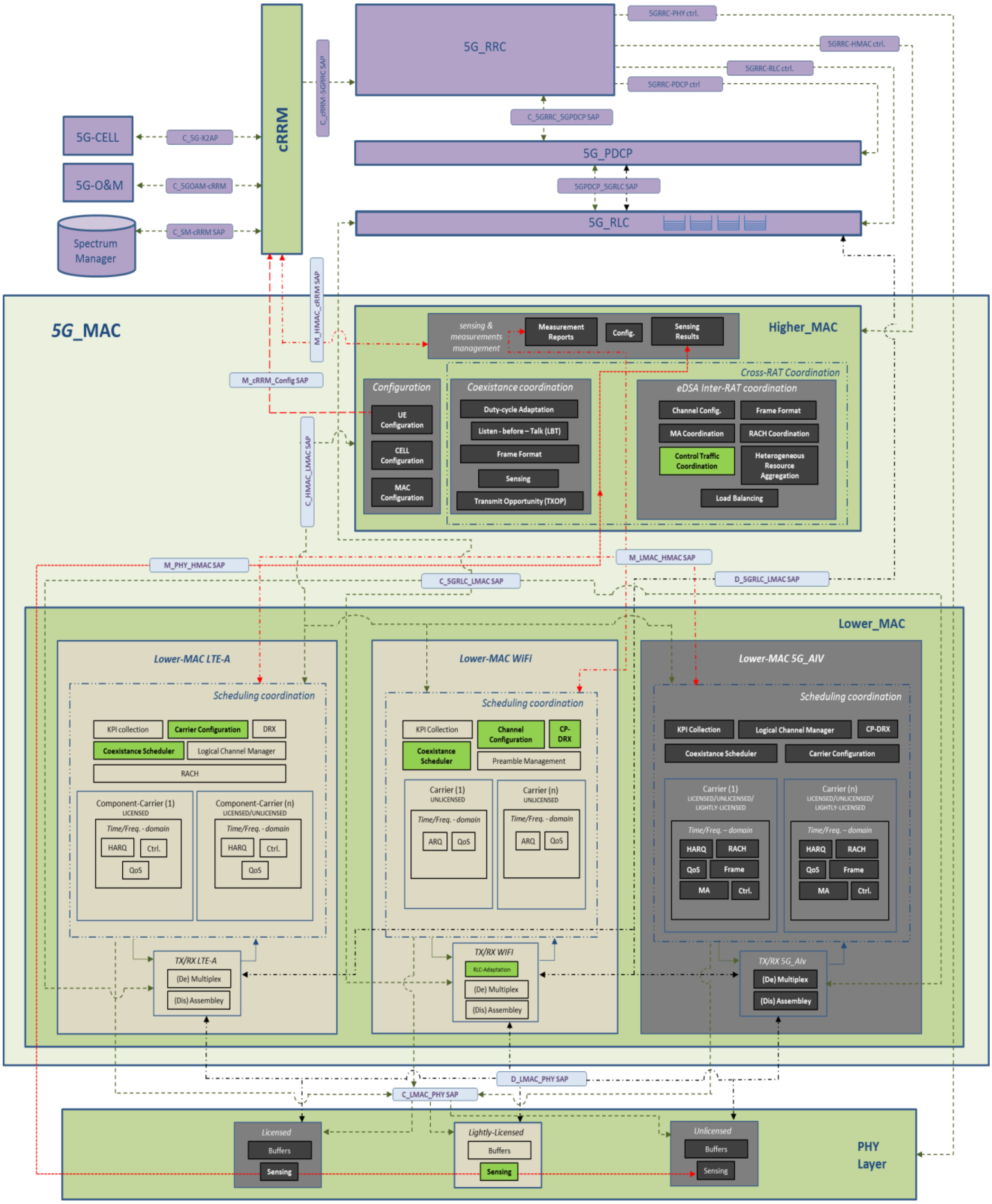


Figure 26: Functional blocks used by the MAC design #2 (SC side)

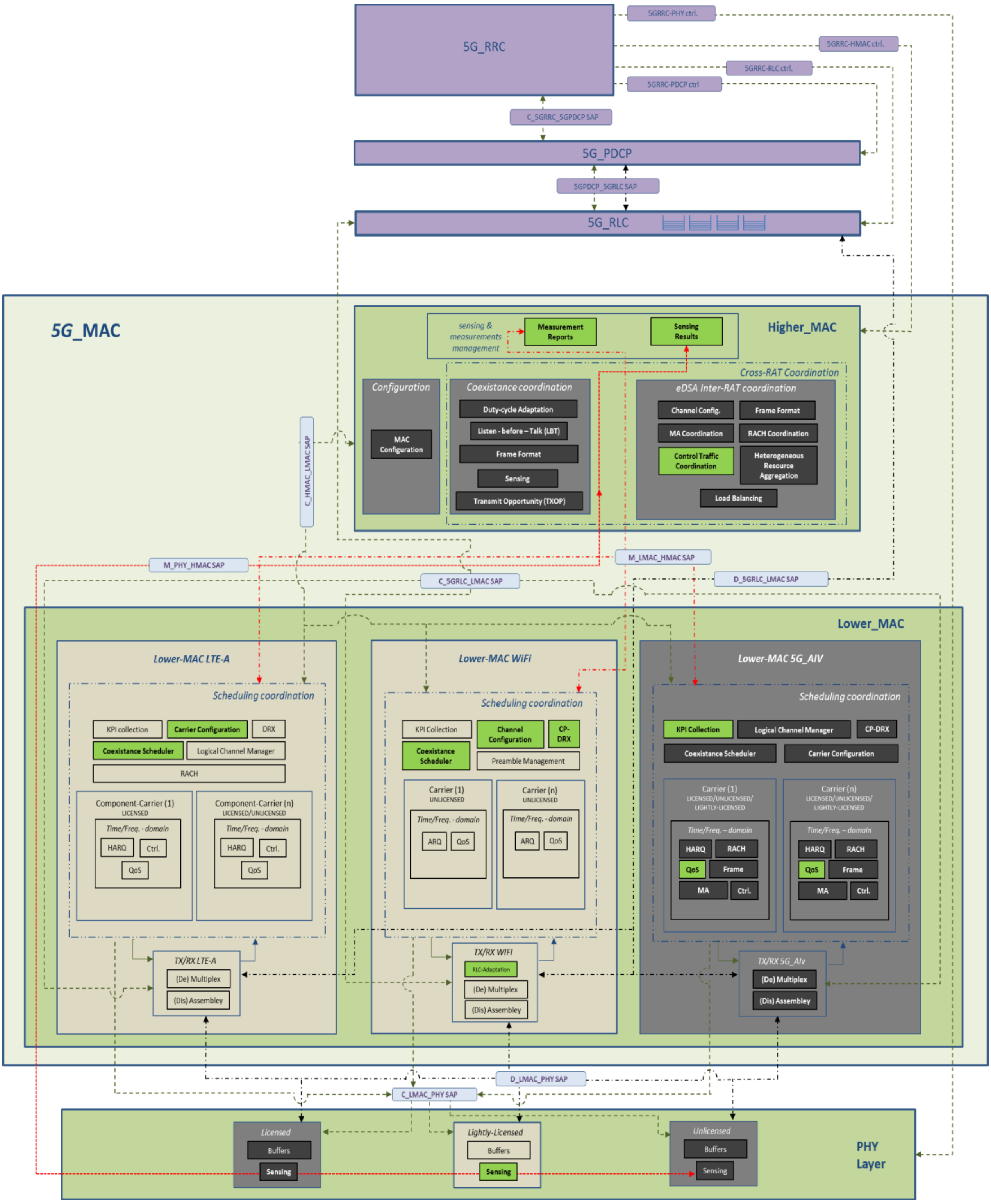


Figure 27: Functional blocks used by the MAC design #2 (UE side)

4.2.2 MAC Services

4.2.2.1 Services provided to upper layers

In addition to services already supported in [6] a number of new services (in Bold) are provided by the extented MAC design to upper layers, mainly related to the support of IoT communication::

- data transfer **using multi-channel operation**
- radio resource allocation, **dependingon the traffic patterns**

4.2.2.2 Services expected from physical layer

The physical layer services provided to the MAC sublayer remain unchanged, as identified in [6], namely:

- Multichannel uplink and downlink transmission
- Frame transmission for both normal and burst modes;
- Frame reception for both normal and burst modes;
- Header error indication for PHY and MAC header;
- Clear channel assessment for estimation of medium activity.

4.2.3 MAC Functions

The following functions are added to standardized MAC layers for achieving eDSA claimed in SPEED-5G project:

- dynamically support carrier aggregation configurations based on the KPIs and QoS
- enhanced spectrum usage with Licensed Shared Access (LSA) and coexistence techniques
- support of massive IoTs deployments
- dynamically configure the control region in eMMB and UDN scenarios
- semi-static control region configuration using a Discontinous Reception (DRX) approach
- 3D allocation resource time – frequency – code scheduler for NOMA procedures
- scheduler QoS update in real time per traffic type
- MOCN by default reducing network deployments

The location of all functions and their relevance for uplink and downlink respectively is illustrated in Table 16 (new functions are highlighted in Bold)

Table 16: MAC function location and direction association for design #2

MAC function	UE	eNB	Downlink	Uplink
Control message for Carrier aggretation (re)configuration	X		X	X
		X	X	X
Usage of the appropriated channel for achieve minimum QoS	X			X
		X	X	
Control message for semi-static static scheduling on IoT sensors	X			
		X	X	
Semi-static scheling for IoT sensors	X			X
		X	X	
Control region configuration	X		X	X
		X	X	X
Control message for semi-static control region applicability	X		X	X
		X	X	X
Time – Frequency – Code configuration		X	X	
Traffic type QoS update		X	X	

4.2.4 Protocol Details

This section provides information on the proposed MAC protocol design and operation.

4.2.4.1 Frame Design and Structure

The basic frame structure and timing for frame exchange, is is aligned with and compliant to the LTE design specified in [47].

4.2.4.2 Multiple Access

The multiple access method used in this design is compliant to the LTE design specified in [6].

4.2.4.3 Control Channels/Frames

The control channel design adopted in this design is compliant to the LTE design specified in [48]-[49].

4.2.4.4 Resource access (RACH design)

The RACH method used in this design is compliant to the LTE mechanisms specified in [44].

4.2.4.5 Heterogeneous Resource Aggregation

The MAC layer is configured by RRM entity indicating the bands allowed to be used for CA. The configuration is received at higher-MAC which configures its algorithms into the eDSA inter-RAT coordination accordantly. Then, the higher-MAC updates the lower-MAC with the different component carriers that should be activated. Each component carrier will be used for a specific traffic type. The main goals of CA are:

- Increase network capacity
- QoS ensured by an appropriate RRM configuration and the lower-MAC QoS functionalities

Figure 28 shows several CA options where the schedulers in the lower-MAC are responsible to allocate resources into a specific frequency or band per UE. Option 1 and 2 do CA into the same band in a contiguous or non-contiguous frequency. In option 3, the CA is done on another band. For instance, option 3 may combine two different RATs, one operating into a licensed band as LTE (red square) and another one operating into an unlicensed band as WiFi (blue square). Option 3 i.e., shows how the SPEED-5G eDSA concept allows to operate over the licensed band, instance using LTE on band 3 and 7. LTE networks, plus in an unlicensed band simultaneously.

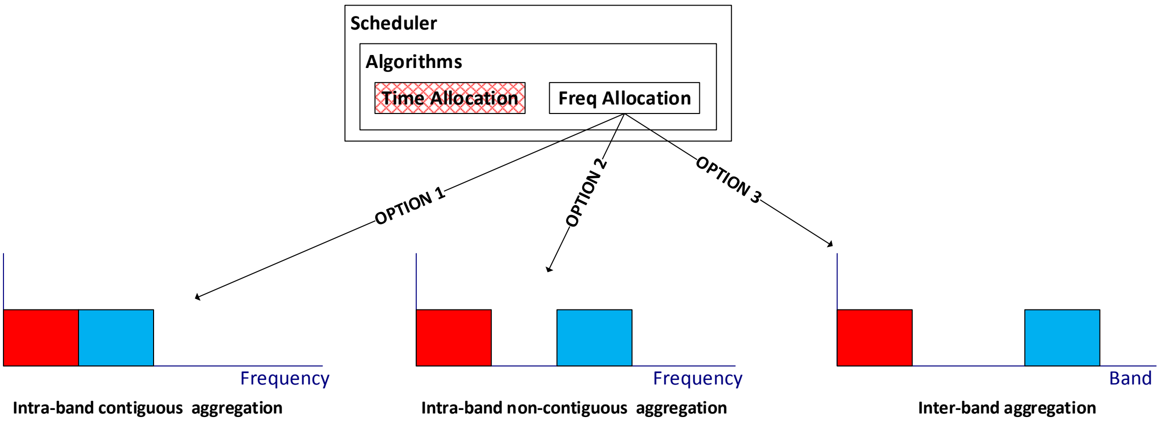


Figure 28: CA options

The RRM required data includes:

- Component carriers to be used
- Traffic type associated to each carrier
- RAT to be used in each component carrier
- Coexistence parameters if a component carrier uses lightly licensed or unlicensed spectrum band
- Period of time where the configuration has to be applied

The cell is responsible to configure each connected UE, and once the UE is configured, the new CA configuration can be applied when the UE confirms that it has received configuration successfully. The network and the UE have to be synchronized in order to simultaneously apply the CA configuration. Synchronization between the two is required for avoiding any temporal mismatch.

In a 5G network, the UE may be attached to more than one cell. Then, there will be a probability that these cells are under the management of different RRMs. In the same way as before, only one cell is responsible to configure the UE but which cell, is decided at RRM level and this procedure is out of scope in this document.

Finally, in order to avoid unnecessary messages. The RRM entity will include the period of time where the CA configuration is considered valid. Including this period of time, the deactivation message is avoided. The deactivation message has to be considered in any case. This message allows to reset current configuration when required without the requirement to end the defined period of time.

4.2.5 MAC procedures

MAC procedures used in this design are compliant to the LTE MAC, as specified in [6].

4.2.6 New Features in MAC design #2

4.2.6.1 Multi-RAT and multi-channel operation

The proposed MAC design is capable of using more than one RAT simultaneously. This solution makes RAT selection transparent to the end-user. Current standardized procedures in 3GPP Rel.13 like LWA or LWIP are natively supported by the novel proposed MAC framework through the new definition of the LTE and WiFi scheduling coordination. The schedulers are therefore capable of dealing with both (licensed & unlicensed) traffic types. The cRRM is the responsible for selection of the most appropriate procedures (for eDSA).

The received cRRM message for multi-RAT and multi-channel configuration contains:

- The RATs to be activated or deactivated in case they have to be switched off
- Frequency or channel per RAT
- Period of time to indicate the new configuration is valid
- Required parameters for coexistence purposes if lightly license or unlicensed channel access is required

The message is received by the eDSA *inter-RAT coordination* entity located at the higher-MAC. The internal algorithms activate and configure the lower-MAC scheduler(s) for coexistence procedures.

The *valid configuration time* value reduces the number of required messages between RRM and MAC layers. In cases when an extra RAT is required for a specific period of time, this value avoids the deactivation message. The time value is also transmitted to lower-MAC in order to automatically deactivate (for cloud computing and virtualized solutions) the schedulers. When the multi-RAT and multi-channel configuration has to be applied for an indefinite period of time, a reserved value is used.

The multi-channel usage, in collaboration with the multi-RAT, allows association with a RAT on specific frequency/channel, leading to increase in the total throughput and an efficient spectrum usage, that is the main SPEED-5G goal. This idea opens a new way to configure the lower-MAC for allocating resources considering the following matrix: RAT | frequency | traffic type | QoS.

This solution requires common security coordination between RATs in a centralized way and transparently from user point of view to ensure that the device is capable of connecting to each available RAT. For instance, the idea is that since the user may not know the password of the WiFi network since it is globally managed by a security entity, the device may be re-scheduled considering the proposed matrix. If the common security entity does not exist, the device may be not able to access all available RATs thus, the RRM entity has to know to which RATs the device is authorized to access. How this common security is achieved is out of the SPEED-5G.

4.2.6.2 Semi-static IoT scheduling

In a broadband wireless scenario, most of the IoTs devices may be categorized as wearable or sensors. The market of wearables which track human habits is becoming popular. Nowadays, wearables are linked to the mobile device which is responsible to upload the data to the cloud. SPEED-5G envisions natively supporting wearables and sensors over a licensed band which can directly send data to the network. For instance, in addition to this, current technologies as ZigBee [22] should be natively supported in the proposed MAC ensuring backwards compatibility. ZigBee is a wireless high level protocol used to send a secured low throughput transmission with low power consumption. In any case, the MAC and its upper and lower interfaces have to be ready to support any kinds of IoT configuration and communications.

Assuming a scenario with massive sensors and wearables deployment, this MAC design proposes a semi-static IoT scheduling concept that avoids collisions in ultra-dense IoTs deployment. The idea is that sensors and wearables send its data to the network with pre-configured UL scheduling grants required, for instance, in LTE networks. This concept is similar to the GSM scheduling process where each UE has reserved its own time slot. In order to do it, when each sensor starts, a fix pre-scheduled information is transmitted from the cell to the IoT. This kind of IoTs do not require the ACK message from the cell to the IoTs so, if the KPIs have a relevant importance since is the fastest way to identify configuration issues.

For sensors that send data through licensed spectrum, they are configured when they start including when it has to start the transmission, the timing advance for synchronization procedures, and the transmission period. Considering all these requisites, the RRM sends the following information:

- Frequency where the sensors operate
- List of sensor types which has to report data
- Transmission periodicity per sensor type
- RAT per sensor type

This concept has multiple advantages. The principal one is that the sensor is connected into the network but not necessary attached into a specific cell considering. From the sensor or wearable point of view, the multiple cells network is considered as a single one, creating a cloud of cells where each one may receive the data. Figure 29 shows the concept of small cell cloud and also, how the region dedicated to control may be used to send device data as everything is pre-configured.

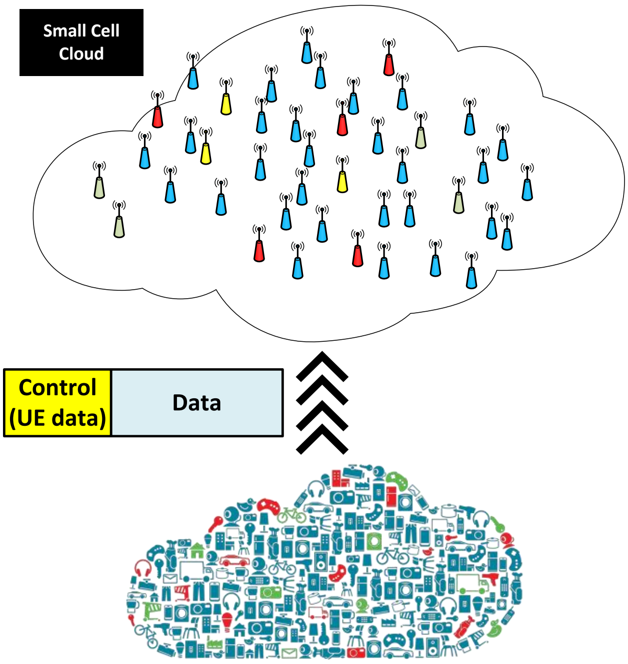


Figure 29: Small Cell concept

On the other hand, the UL transmission has to be synchronized and each sensor has to have the same reference time in order to avoid collision. As the IoTs are connected to the network, they may get the network time. Another issue to be resolved is the configured timing advance when the IoT is moving all around the network coverage. D5.2 deliverable will provide more details about how the timing advance is providing using the minimum number of DL control messages.

4.2.6.3 Configurable control data region

The overall SPEED-5G eDSA objective is the optimal usage of the spectrum resources. Some of the proposed techniques (e.g. carrier-aggregation, multi-RAT and multi-channel usage and 3D-scheduling) require new control information on the data plane which adds an overhead. The overhead requires reserving more physical radio resources. In the past, the control region has been perfectly defined so the devices perfectly know where the control region is allocated.

SPEED-5G proposes a configurable control region where the size depends on the control data to be sent. The main goal of this idea is to be able to increase the data plane region for increasing the total throughput. The main inconvenience of this proposal is that each device has to be synchronized with the network in order to know where the control region is. Considering this, the control plane region may not be modified each TTI, it has to be configured for a period of time where the control area remains static. When a new device is connected, the network has to configure it appropriately. Thus, the connection reconfiguration message from the cell to the device should be updated with this information. Periodically, the control region will be modified and therefore the connection reconfiguration message is to contain a predefined pattern control region pattern which avoids control plane messages.

This MAC design assumes the usage of FBMC where the control region contains pilot and synchronization symbols as well as whitespaces. The idea of the algorithm is to use these whitespaces to transmit the control messages leaving the data region fully free to be used exclusively for the user-data plane. The number of whitespaces and when they are available in FBMC is fully linked with the PHY but, as the MAC and PHY works in a collaborative way, the MAC layer also knows the whitespaces and when they appear. For that reason, is possible to know when the control data may be transmitted and the amount of data capable to be transmitted. On licensed spectrum, the number of pilot symbols, called *P*, is variable and depends on the channel status. The space between pilot symbols used to transmit the synchronization symbols, is also variable, called *D*. Ideally, *P* has to be as small as possible and *D*, on the contrary, as big as possible.

Figure 28 shows how the control region and the TTI may vary. The variability of these parameters is under a patent process and for that reason, the complete procedure will be provided in the following D5.2 deliverable.

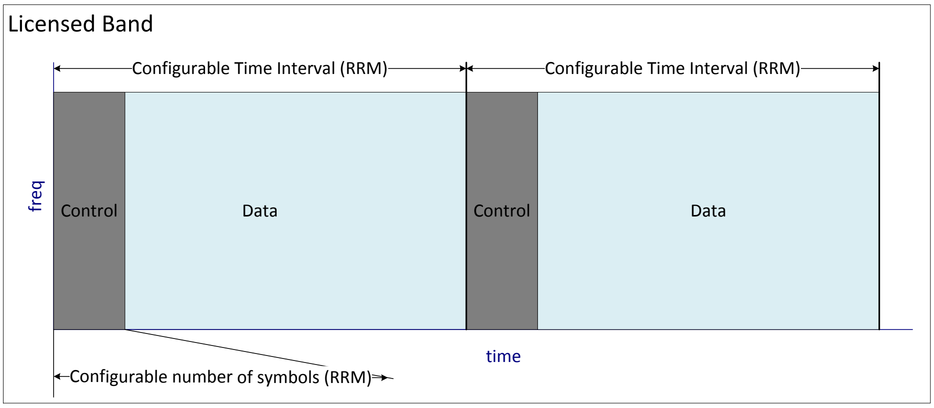


Figure 30: Frame on licensed band using FBMC on licensed band

Figure 31 shows the pilot, the synchronization symbols, and the whitespaces. The tasks on future deliverables for licensed band focus on checking if the pilot and synchronization symbols do not disturb the control plane data located into the whitespaces, and to establish the optimal configurations of *P* and *D* that allows having as much resources dedicated for the user-plane data as possible. The optimal value for *D* will be investigated in order to know if it can be variable into the same frame.

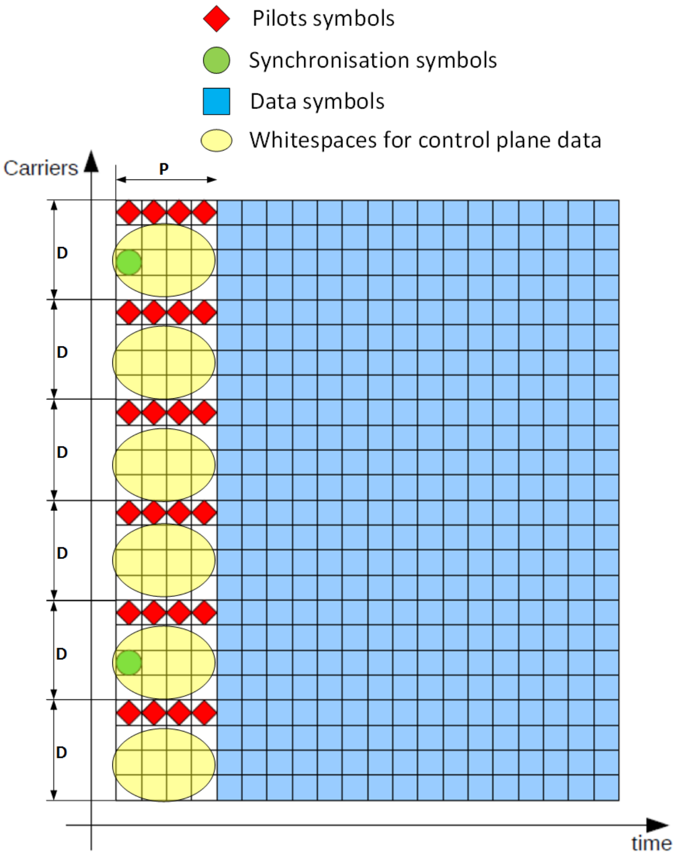


Figure 31: Frame with whitespaces for control data using FBMC on licensed band

Further research is required in order to know the reconfiguration period. Depending on this period, the functionality to obtain *P* and *D* may be delegated to a centralized RRM or it has to be done into the MAC. How the *P* and *D* are notified to the UEs is out of scope as well as how the entity who measures them notifies the values to configuration layers like RRC in LTE.

When *P* and *D* are calculated into RRM, it is the higher-MAC *Channel Configuration* module that configures the scheduler to appropriately schedule the control messages into the whitespaces of the control region. The final *P* and *D* are fully related with the total amount of user data that can be delivered. Then, each configuration implies, for instance, a new LUT to be used by the lower-MAC schedulers.

4.2.6.4 Control data period with DRX

Current RAT does not allow informing the UEs when the next control messages will be send. For that reason, the UEs have to be permanently listening the channel in order to find control data send to them. We proposes to use the same DRX concept as in LTE but applied on the control plane messages. The idea is that the UE listens only the control messages when the DRX cycle is ON. Other case, the UEs may switch off its radio or use this region, previously used to send control data, to receive data plane messages.

Depending on the final solution, there two main advantages: reduce the UE battery consumption or, improve the spectrum usage. This procedure requires changes on the current air interface between the cell and the devices and new mechanism on the cell and the UE side.

RRM is the responsible for defining the CP-DRX cycles which the higher-MAC receives. Then, the higher-MAC sends the required information to the lower-MAC who finally is the responsible to manage the cycles keeping the synchronization with the devices. The required RRM data contains:

- The short and long CP-DRX cycle per device type
- Period of time where the same CP-DRX applies

One of the main issues of this solution is a desynchronization between the cell and the device. When it occurs, the connection will be completely lost. In order to avoid it, the same steps and parameters used for standardized DRX have to be used in this case. For instance, on duration timers, DRX inactivity timers, DRX retransmission timers, long DRX cycles, short cycles and short cycle timers.

4.2.6.5 3D-Scheduling support

3D-Scheduling in support of NOMA implies that devices can be scheduled in time | frequency | power/ code domains, creating a 3D matrix where different UEs may be allocated. NOMA concept requires changes on the current devices since they require the code to be able to decode the data send to them. The MAC of the new devices has to be ready to schedule in time/frequency/code also for the UL link. The cell and device physical layer have to be updated and configured properly in order to support NOMA. The API between the MAC and the PHY layer has to be updated including this information and the period where this information is considered valid. The way the new devices are configured may use the CP-DRX concept proposed in 4.2.6.4 where the same frequency – code pattern applies for a period of time.

4.3 MAC design #3: Decentralized dynamic TDD MAC (DSC-MAC) for ultra-dense networks

This section introduces a new MAC design approach in order to support high-capacity broadband wireless access over the ultra-dense networks (UDNs), termed “DCS-MAC” .The UDNs, seen as a key enabler of the next-generation mobile networks, are expected to be installed without traditional RF planning and proper site selection in many cases. Lack of such proper planning of the network deployment can cause excessive inter-cell interference in the UDNs. In addition, as SCs (i.e., constituents of the UDNs) are foreseen to operate in licensed as well as unlicensed spectrum bands, inter-system and inter-tier interference becomes a major concern. A small size of cells in ultra-dense networks may result in a large growth of signalling regarding the mobility management.

Considering such challenges, the DCS-MAC protocol is designed to enable efficient operation in scenarios characterized by dense planned and unplanned deployments of SC base stations operating on licensed as well as unlicensed spectrum bands. In some extend, this MAC approach can be seen as a default configuration of SCs, which could be used in the case when the connection with the virtualized edge RRM functions is not available (see [2]). In this situation, the self-optimizing feature of this approach is an effective way to cope with load and interference experience in ultra-dense networks.

The proposed DCS-MAC protocol is wave-form independent and supports the eDSA concept by allowing contiguous and non-contiguous channel aggregation, as well as seamless handovers between licensed, unlicensed and lightly licensed spectrum. In addition, this MAC introduces an autonomous mechanism for efficient monitoring of different channels which provide necessary information for proper assessment of channel status (while limiting the power consumption). Thus, dynamic channel selection becomes the core of the proposed MAC, with the main task of preventing QoS degradation resulting from high level of interference and simplifying network planning. Moreover, channel aggregation is also utilized to mitigate interference.

The proposed spectrum agile MAC protocol is based on the dynamic channel selection principle. Using a light weight channel selection strategy, a transmitting node dynamically selects the interference free channel based on the spectral characteristics and sends a preamble followed by the data. Unlike single channel MACs, a receiving node sequentially scans all the frequency channels in the available pool and is able to detect activity in the channel being used by the transmitter. At the same time, the receiving node is able to ascertain the presence of external interferers and their strengths. Without any external information on spectrum characteristics, DCS-MAC uses channel selection operation and adopts it operation for both licensed and unlicensed bands. In the proposed DCS-MAC, licensed and unlicensed/lightly-licensed spectrum/resources are all managed by the same mechanism. **In addition to basic features (as outlined in section 4.3.4) the following novel features are supported by and integrated into the DCS-MAC design:**

- Dynamic channel selection
- Multi-RAT and multi-channel operation
- Dynamic UL/DL resource allocation
- Decentralized decision-making
- Support for Cluster-based architecture (higher and lower-MAC)

4.3.1 Relation to the MAC Framework

The mapping of the proposed MAC design to the SPEED-5G MAC framework (in figure 2), is depicted in Figure 32 and Figure 33 below:

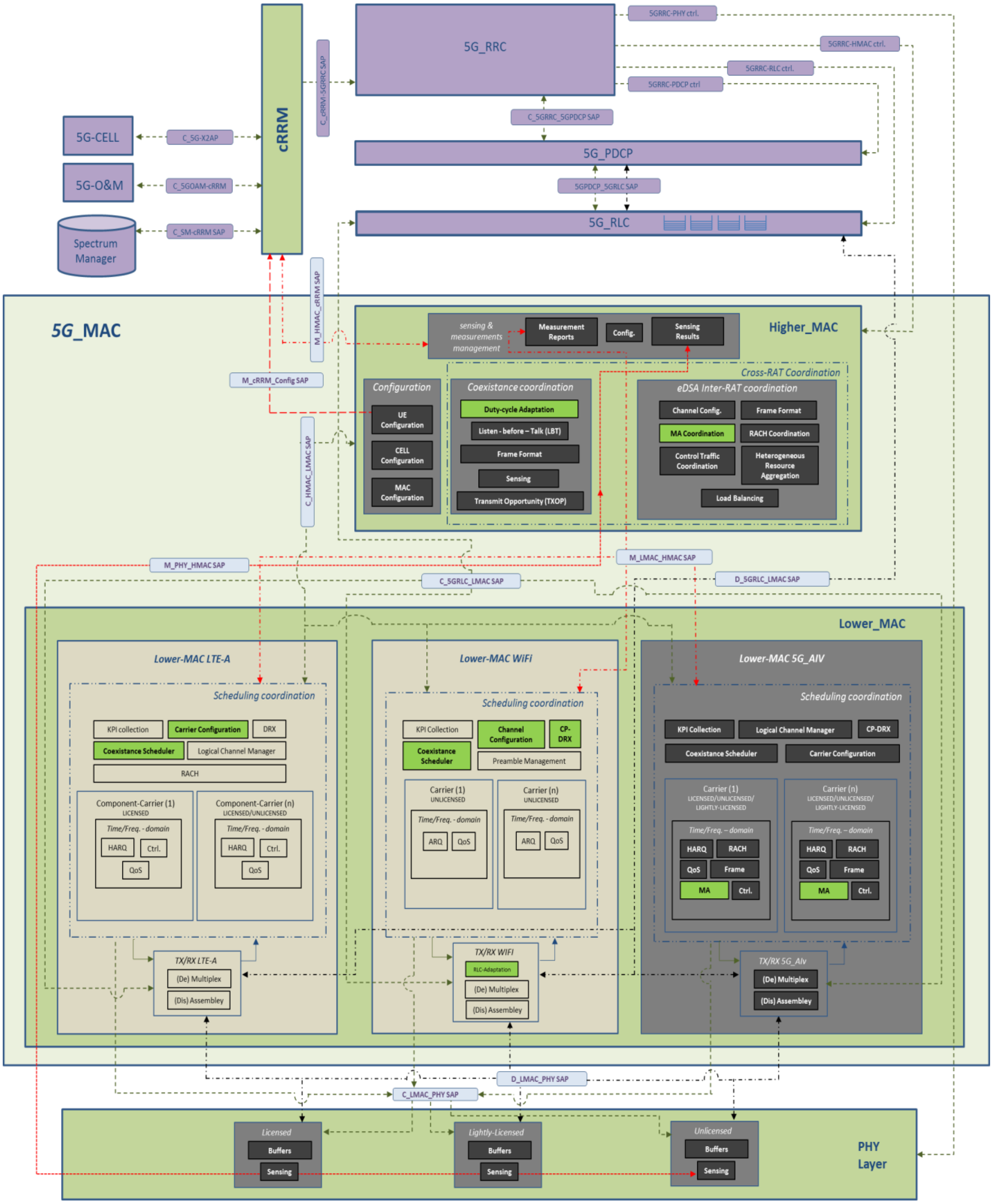


Figure 32: Functional blocks used by the MAC design (SC-side)

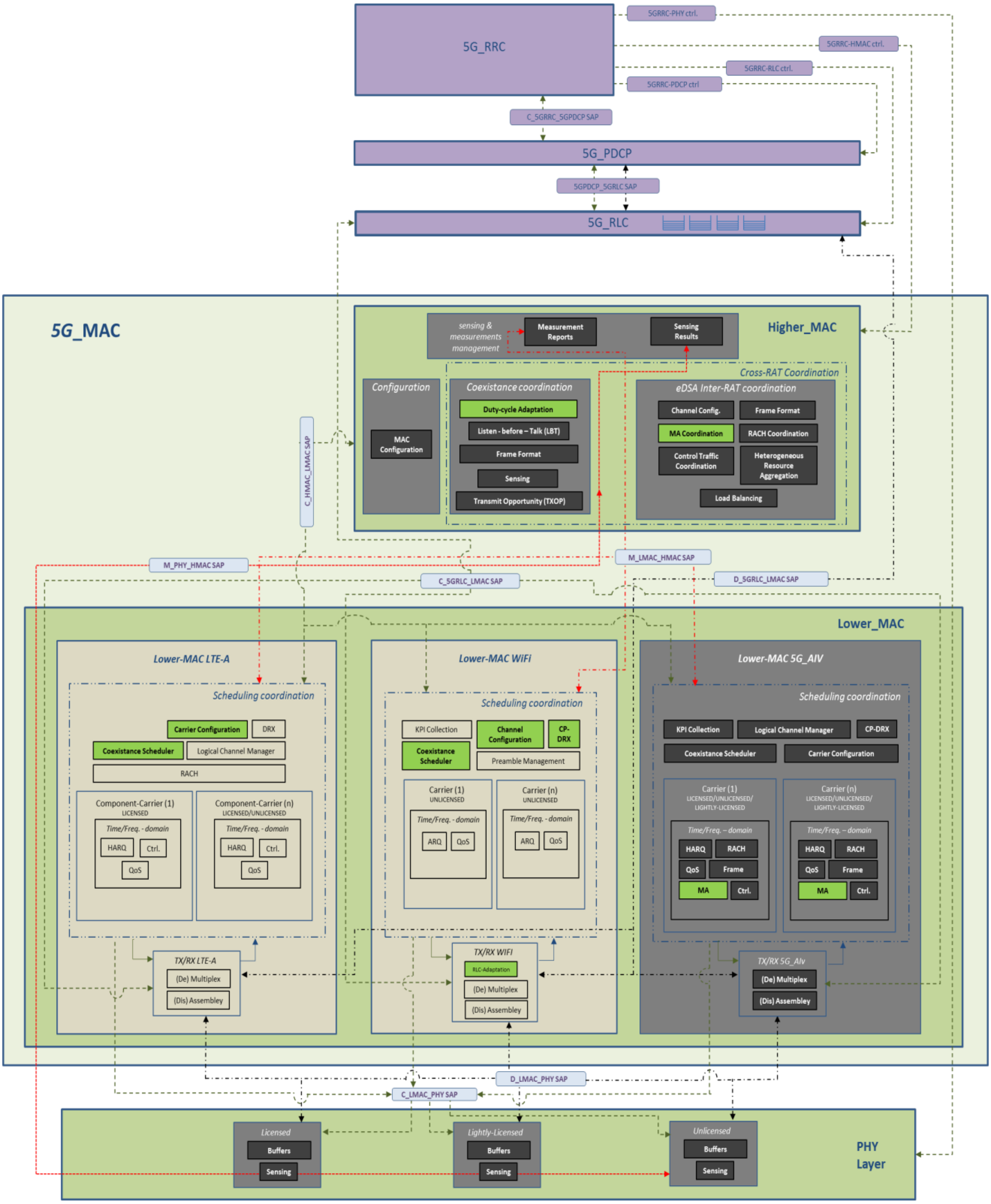


Figure 33: Functional blocks used by the MAC design (UE-side)

4.3.2 MAC Services

4.3.2.1 Services provided to upper layers

The different services provided by MAC sublayer to upper layers are:

- **Data transfer**: The MAC layer can be requested to transmit or receive data over a specific logical channel. In case there is no active bearer avialable, MAC is responsible for establishing a new bearer before transmission can take place.
- **Channel quality measurements**: The MAC layer can be requested to provide channel quality measurements for specific channels. The requested measurements can be used by higher layers e.g. to affect resource allocation in other systems.
- **Channel selection policies**: The upper layers may use this service to affect channel selection policies used by the MAC. The channel selection policies may be changed, e.g., as a result of a cRRM request (e.g. some channels may need to be excluded from selection).
- **Channel access policies:** The upper layers may use this service to affect access policies and scanning/hopping sequence selection policies. The service may be used, e.g., in a resposne to a cRRM request.

4.3.2.2 Services expected from physical layer

The physical layer provides the following services to MAC:

- **Data transfer**: The physical layer can be requested to transmit or receive data over a specific physical channel. The characteristics of a physical channel are defined by its transport format (i.e. modulation and conding scheme), frequency channel number, time slot number and channel bandwidth.
- **Timing adjustment**: The physical layer can be requested to shorten or lengthen a single frame by a certain period. The service is used by terminals during the synchronization with their serving base stations and by base stations to achieve synchronization with neighbouring base stations.
- **Measurements of signal strength and channel quality**: The physical layer can be requested to conduct measurements required for physical channel (radio resource) selection and for monitoring quality of channels for future use.
- **Preamble detection**: The physical layer can be requested to monitor different frequency channel is a search of a preamble to acquire slot synchronization during the initial scanning.

4.3.3 MAC Functions

The different functions supported by the MAC sublayer are:

- mapping between logical channels and physical channels (i.e. bearers);
- multiplexing of broadcast data, control data and higher layer data (from one or different logical channels) onto physical channels (i.e. bearers) to be delivered to the physical layer;
- demultiplexing of broadcast data, control data and higher layer data (from one or different logical channels) from physical channels (i.e. bearers) delivered from the physical layer;
- Radio resource selection for bearer establishment;
- error correction through HARQ;
- selection of transmission format;
- priority handling between UEs;
- priority handling between logical channels of one MAC entity;
- scanning/hopping seqence selection;
- multi-channel quality monitoring;

The location of the different functions and their relevance for uplink and downlink respectively is illustrated in Table 17.

Table 17: MAC function location and direction associationfor design #3

MAC function	UE	BS	Downlink	Uplink
Mapping between logical channels and physical channels	X		X	X
		X	X	X
Multiplexing	X			X
		X	X	
Demultiplexing	X		X	
		X		X
Error correction through HARQ	X		X	X
		X	X	X
Transport Format Selection		X	X	O[1]
	X			X
Radio Resource Selection for bearer establishment	X			X
		X	X	O[1]
Scanning/Hopping Seqence Selection		X	X	X
Priority handling between UEs		X	X	X
Priority handling between logical channels of one MAC entity		X	X	X
Multi-channel quality monitoring	X		X	X
		X	X	X
Note1: In some situations it may be beneficail for BS to make the final decision				

4.3.4 Protocol Details

This section provides basic information on the proposed DCS-MAC.

4.3.4.1 Frame Design and Structure

The frame structure for the proposed MAC is depicted in Figure 34. Although not depicted in the figure, the slot lengths can vary, thus affecting the number of slots per frame. The slot lengths (and as a result, the number of slots per frame) may change depending on the bandwidth of frequency channels, the licensing regime of the spectrum band, traffic type and channel load (the mechanisms for dynamic adaptation of the slot lengths are currently under investigation). The frame length is set to be 10ms, although other lengths are considered for future study.

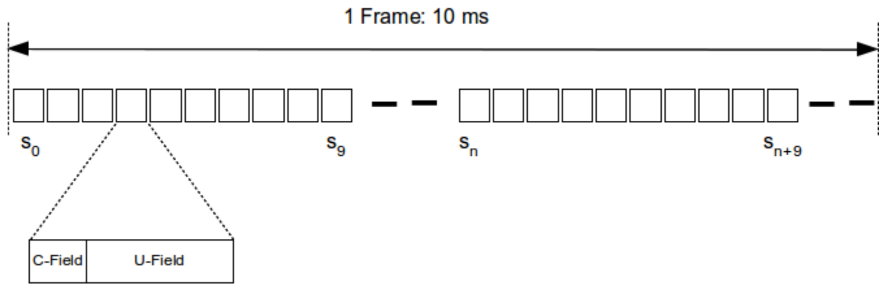


Figure 34: Frame and slot structure

As see above, each slot in a frame is subdivided into a control part (C-Field) and a user data part (U-Field). In order to limit the overhead related to the control part, we allow the slot lengths to be dynamically changed (e.g. depending on the interference conditions). The length of the control part is variable and depends on the frequency channel bandwidth.

Several frames constitute a multi-frame (see Figure 35). The multi-frame length is related to the amount of common control information which needs to be broadcasted by base stations which is also a topic of an ongoing study.

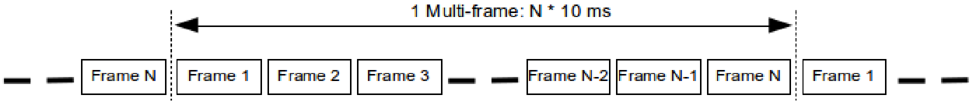


Figure 35: Multi-frame structure

4.3.4.2 Multiple Access

As indicated in [35], technology neutral spectrum is a global trend. This trend, along with the recent decisions of the Federal Communications Commission (FCC) [36] and the Office of Communications (Ofcom) [39] to relax regulations and allow temporal access on a secondary basis to unused TV frequency bands (commonly called TV White Spaces) may lead in the near future to a rapid growth in deployment of radio systems operating in multiple spectrum bands. In order to fully exploit the potential of additional spectrum a system which is capable of efficient operation in multi-channel and multi-band environment is desirable.

The multiple access of the proposed MAC is based on a combination of multi-channel operation, Time Division Multiple Access (TDMA) and Time Division Duplexing (TDD) and is designed to fully exploit the potential of additional spectrum. As shown in the next sections, many of valuable characteristics of the proposed MAC arise because of the highly flexible nature of such combination. The combination of a frequency channel and a time slot is defined as a **physical channel** and is the smallest amount of resource which can be allocated for transmission.

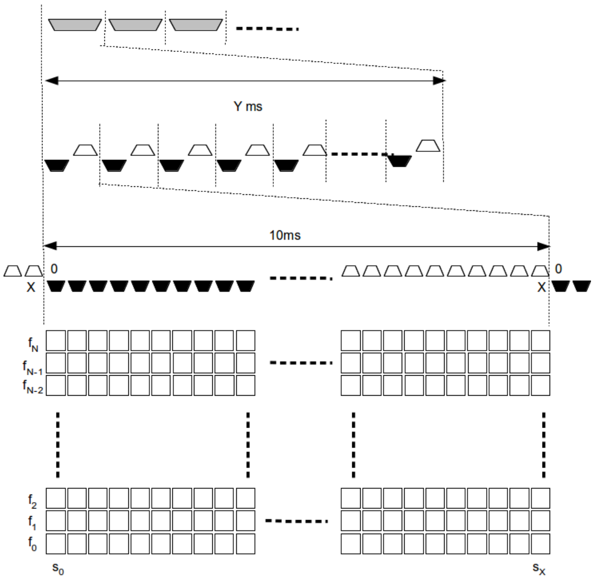


Figure 36: Multiple access and physical channel structure (Physical channel = time slot + frequency channel combination)

Time slotted access - In general, systems can be divided as systems with asynchronous and synchronous access. One of the most well-known systems using the asynchronous access is the IEEE 802.11. The main characteristic of such a system is the possibility of transmitting data at any time, given that certain criteria are met (e.g. maximum energy level in the channel in case of IEEE 802.11). As a result of this, base stations as well as terminals need to continuously monitor the channel, synchronize and process all transmitted frames (reception of a frame can be ceased not sooner than before it is possible to determine the address of the recipient). As seen in the Figure 37, this may lead to so called “stronger-last collision problem” which may significantly degrade system performance. The problem appears when a receiver fails to synchronize with a transmission because it is already synchronized with a significantly weaker signal which was not intended for it.

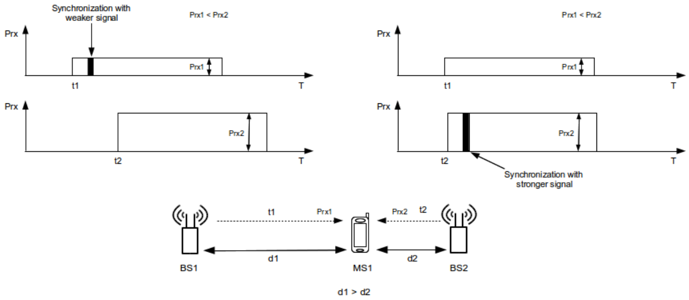


Figure 37: “Stronger-last collision problem” in asynchronous access based systems (left) and synchronous access based systems.

In order to eliminate this problem, a synchronous TDMA access is adopted in the proposed MAC protocol, meaning that each frequency channel is fragmented into time slots which can be accessed only at specific points in time (in synchronous systems we always synchronize with the strongest signal). In contrast to the typical TDMA solutions used in existing cellular systems (e.g. GSM), time advancing which compensate for the propagation delay, thus eliminating inter-slot interference, is not used in the proposed MAC. Instead, the propagation delay is compensated by shortening transmission in each slot. This simplifies the design and reduces the delay of accessing the network by eliminating the need for dedicated RACH related procedures. This allows e.g. for faster inter-cell handovers. Additionally, the proposed scheme eliminates the problem of inter-slot interference between base stations and between terminals which cannot be eliminated by the time advancing (see Figure 38). Another advantage is related with less straighten requirements for inter-cell synchronization. It needs to be emphasized here that due to the small radius of cells (and thus short propagation delays), the overhead related with the shortening of transmissions is not significant. It is also worth highlighting that the proposed access scheme is based on a non-continuous transmission. This means that each transmission/burst needs to carry sufficient information for successful decoding and demodulation by a receiver, thus essentially allowing terminals and base stations to receive transmissions from an arbitrary source node.

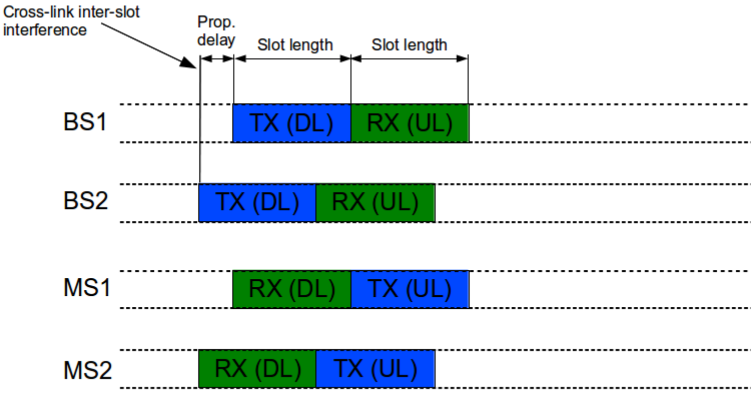


Figure 38: Cross-link inter-slot interference

As a byproduct of using TDMA, the proposed MAC enables QoS support and allows for simultaneous connectivity with more than one base station (by allocating additional time slots for the same connection). This allows terminals to exploit the base station diversity and thus improve utilization of resources.

Duplexing scheme - A duplexing scheme describes how uplink and downlink transmissions are handled by the system. The duplexing scheme used by the proposed MAC separates uplink transmissions from downlink transmissions in the time domain. The separation between uplink and downlink traffic is static and is equal to the half of the length of the frame. As seen in Figure 40, this means that for every downlink slot there is a pre-allocated uplink slot.

There are several reasons for using such a scheme. The first reason is related to the multi-channel hidden-terminal problem and the need for a proper way of handling this problem in case of bi-directional links/bearers which are used to convey dedicated control traffic between a base station and a terminal. The multi-channel hidden-terminal problem appears in multi-channel MAC protocols when a node switches to a new frequency channel after a reservation of this channel is made by another node. Due to the inability to determine whether a given channel is occupied, the node initiates a transmission which interferes with an ongoing transmission. This problem can be solved by employing the static separation between uplink and downlink transmission for bi-directional links/bearers. As mentioned, the static separation means that every physical channel is pre-allocated with a physical channel for transmission in the opposite direction. This means that a node can always infer which physical channels needs to be monitored to determine if a given physical channel is not occupied by a bi-directional link, before initiating its own transmission (see Figure 39).

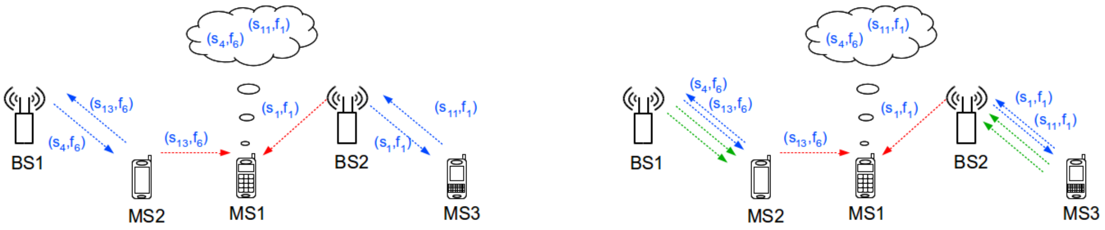


Figure 39: Solution to multi-channel hidden terminal problem for bi-directional links (assuming 20 slots per TDMA frame)

Another reason for using the static separation between uplink and downlink transmission is related with a lower signalling overhead. The static separation in this case allows implicit reservation of slots for downlink transmission (in case of terminal initiated connection) or uplink transmission (in case of BS initiated connection). The proposed separation means also that there is no need for dedicated resources for RACH as the initiating party always knows which channel it should use for receiving the response for its request. The last reason is related to the cluster-based architecture and possible delay requirements imposed by different physical locations of cluster controllers and cluster members.

It needs to be highlighted here that the direction of transmission for all slots can be renegotiated for already ongoing connections or during the connection setup, thus allowing full flexibility in resource allocation. The following figure presents different types of connections which can be established, including single bearer connections (red), multi-bearer symmetric connections (blue), asymmetric downlink connections (green) and asymmetric uplink connections (purple).

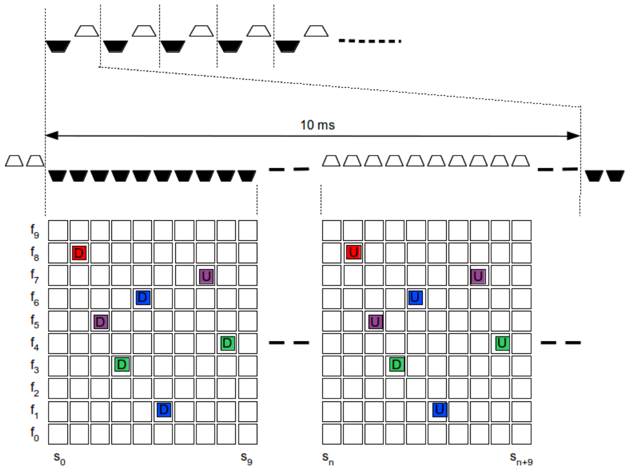


Figure 40: Examples of supported connection types: symmetric link (red), multi-bearer symmetric link (blue), asymmetric downlink (green), asymmetric uplink (magenta)

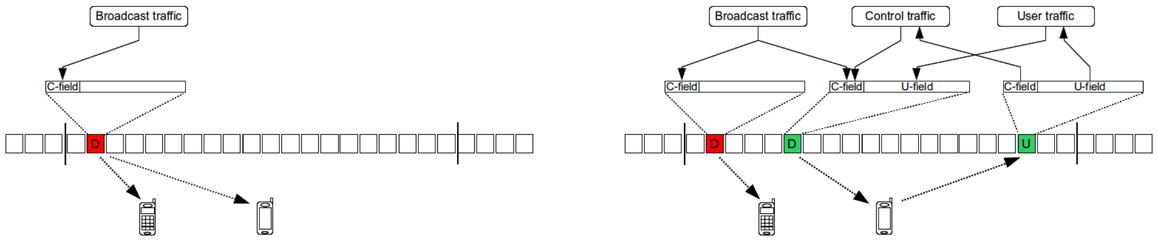
4.3.4.3 Control Channels/Frames

Common Control Channels - The static assignment of resources for common control channels is a common practice in cellular systems. However, such approach may be a source of significant performance degradation due to excessive inter-cell interference in dense network deployments. The performance degradation could be further amplified if a radio system which statically assigns resources for common control channels operated in a shared or unlicensed band (excessive inter-operator and inter-system interference).

In order to mitigate the impact of the interference on such channels, common control channels in the proposed MAC can be multiplexed in frequency and time domain. In addition, the proposed MAC enforces transmission of common system information on all active downlink channels, thus making important control information resistant for accidental or malicious interference and avoiding a single point of failure. This stands in a sharp contrast with typical macro-cellular systems which rely on a single channel for transmission of common system information.

As already mentioned, to limit the overhead related to the transmission of additional information, we allow the slot lengths to be dynamically changed, depending on the interference conditions. In case of high level of interference, the slots would be shorter thus improving the robustness against interference. In other situation, the length of the slots could be extended, thus reducing the overhead (to enable coexistence between nodes operating using different slot lengths, the length of slots which can be used in are predefined).

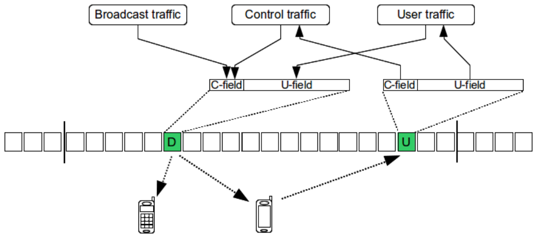
In case there are no active downlink channels (i.e. no active users), a base station establishes a special uni-directional link/bearer to transmit common control information (see Figure 41(a)). To maintain high robustness against interference, the allocation of radio resources for such a bearer changes periodically, or when the quality of the channel degrades (such a change can be also requested by a user). The change in allocation of resources for such a bearer is preceded with information about new resource allocation. The following figures show different options for transmission of common control information.



(a) uni-directional broadcast bearer for common

(b)common control traffic multiplexed with control traffic

dedicated control traffic and uni-directional broadcast bearer



(c)common control traffic multiplexed with dedicated control traffic

Figure 41: Possible configurations for transmission of common control information.

The contents of the common control channels include information about a base station identify, a scanning/hopping sequence adopted by a base station, a number of transceivers operating in a base station, physical channels unavailable for access, supported frequency channels and paging (for users in a power saving mode). This information is time multiplexed with dedicated control traffic (see Figure 41 (b)) and, as already mentioned, transmitted on all active downlink channels. It needs to be highlighted here that in order to indicate the owner of the physical channel allocated for uplink transmission (and at the same time improve the cell discovery), all terminals time multiplex its serving base station identity with dedicated control traffic in the uplink direction.

Dedicated Control Channels - Resources dedicated for control traffic are allocated for each bearer in both directions and carry information relevant for a particular bearer (or connection). In case of a multi-bearer connection one of the bearers is allocated as a pilot bearer which means that by default it carries all connection related control information. The information carried by dedicated control channels include acknowledgements, requests for temporal deviations from scanning/hopping pattern (necessary to reduce delay in accessing a particular physical channel, bearer establishment request/response messages and bearer release messages. It is worth reminding here that dedicated control information is time multiplexed with common control information. To indicate the ownership of the physical channel allocated for uplink transmission and improve the cell discovery, serving base station identity is continuously time multiplexed with dedicated control traffic in the uplink direction.

4.3.4.4 Resource Access (RACH design)

One of the main aspects related to MAC protocol design for cellular networks is the random access channel design. A special design for RACH which differs from a design of other channels is a common practice. One of the main reasons for this is the fact that the existing cellular systems are design for macro cell deployment. This means that RACH has to be designed to accommodate for different range of propagation delays, thus making its design inefficient in terms of resource usage. As a result, dedicated resources need to be allocated for RACH to handle traffic from users which initiate their connections. Proper dimensioning of resources allocated for RACH in such systems is often a problem and if done improperly may lead to inefficient use of resources or long access delays. Additional problem is related with interference. In most of existing systems, RACH is allocated with static resources, similarly to common control channels. This means that RACH may be prone to interference in dense scenarios characterized by irregular deployment (e.g. heterogeneous networks or dense/ultra-dense networks) or when operating in shared bands or technology neutral bands.

In order to alleviate the problem of interference and non-optimal allocation of resources for RACH, in the proposed MAC design we resigned from differentiating between resources dedicated for RACH and other channels (this essentially means that the proposed MAC design does not account for long propagation delays and thus is not suitable for macro cell deployment). One of the main advantages of such approach is that all resources pre-allocated for uplink transmission (see Figure 42) can be potentially used for initiating a new connection. The access to all channels pre-allocated for uplink transmission is facilitated by the continuous scanning of all channels. The scanning is conducted according to a specific scanning/hopping sequence. In order to lower contention between terminals, different scanning/hopping sequences can be adopted by neighboring cells. It is worth reminding here that by increasing the number of transceivers in a base station we are increasing the number of physical channels (i.e. time slot/frequency channel combination) which can be accessed at the same time (the additional transceiver adapts a delayed version of the same hopping/scanning sequence as the first transceiver). This allows us to lower the contention between users in the same cell and provide faster access to desired resources. Finally, the implementation of RACH in a form of a logical channel created by a channel scanning sequence (hopping sequence) allows us to improve resistance against intra-system (i.e. inter-cell interference) and inter-system interference (interference coming from other radio systems operating in the same band) by providing access to all physical channels available for uplink transmission.

Different scanning/hopping sequences can be adopted by a base station. The figure below depicts one possible example of a scanning/hopping sequence in which a transceiver scans one frequency channel per MAC frame. More sophisticated scanning/hopping sequences which intend to minimize contention between users from neighbouring cells are a topic of an ongoing study. It is worth reminding here that, to enable a base station initiated transmission, terminals adapt a delayed version of the same hopping/scanning sequence as their serving base station.

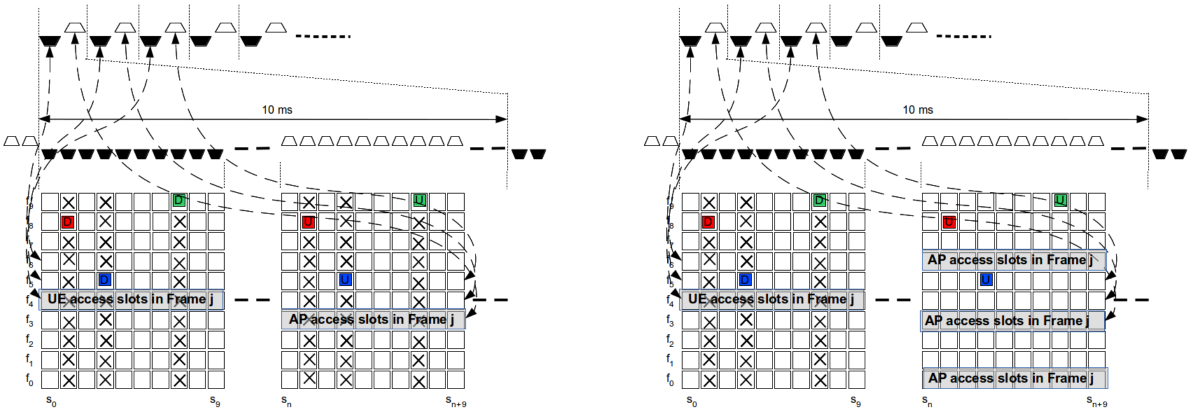


Figure 42: Impact of BS transceiver number on channel access(X – channels unavailable for access)

4.3.4.5 Heterogeneous Resource Aggregation

Channel/Carrier-Aggregation is an important feature which allows increased peak throughput and system capacity, as well as more flexible resource allocation. In most of existing systems channel/carrier-aggregation was developed as an extension in order to cope with a growing demand for traffic. As a result of this, due to the need for backward compatibility, semi-optimal solutions which do not allow for full exploitation of available resources or impose a significant signaling overhead had to be used.

The proposed MAC was designed to natively support the Channel/Carrier Aggregation, thus allowing radio system to optimally exploit additional resources provided by additional resources. Enabling aggregation of additional channel in the proposed MAC is equivalent to adding a new transceiver. The flexibility of resource allocation could be limited only as a result of inability of some transceivers to operate in all supported bands (e.g. transceivers which are capable of operating in multiple bands could be costly).The aggregation feature in the proposed MAC is scalable in the sense that it can potentially support aggregation of arbitrary number of channels with virtually no additional overhead.

4.3.5 MAC procedures

The following section describes several basic procedures supported by the proposed MAC design. The DCS-MAC layer can perform the following procedures:

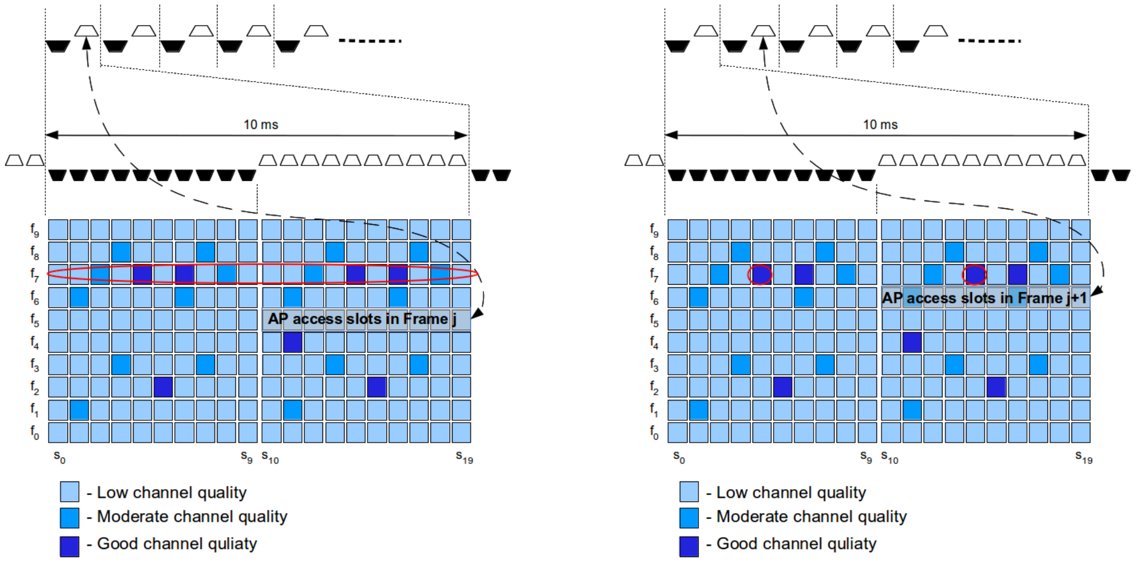
- Pilot bearer establishment procedure
- Non-pilot bearer establishment procedure
- Bearer release procedure
- Base station slot availability indication procedure
- Terminal synchronization/locking procedure
- Base station synchronization/locking procedure
- Channel sequence/hopping alteration procedure
- Slot length alteration procedure
- Paging procedure

4.3.5.1 Pilot bearer establishment procedure

The procedure is always triggered during a connection setup (or inter-cell handover) to establish a bi-directional bearer (called the “pilot bearer”) which is **used for conveying control traffic**. At least one such a bearer needs to be maintained for every active connection. The procedure is the same for terminal-initiated and base station-initiated bearer establishment and consists of two parts: channel selection and establishment execution.

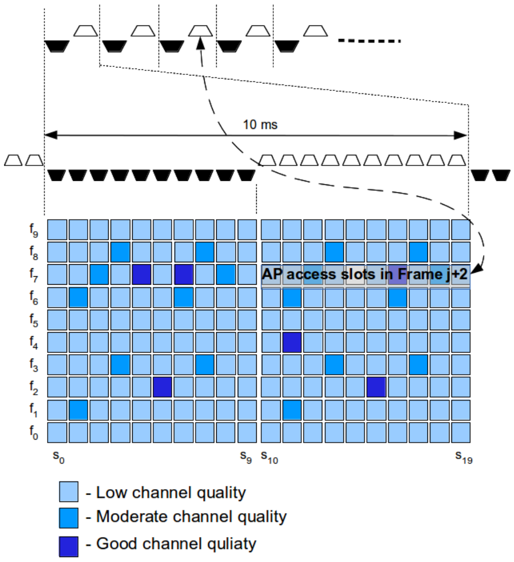
The channel selection part consists of four steps described below.

1. Select the physical channel with the best quality (e.g. minimum level of interference) which does not breach any of the channel access requirements and is accessible not sooner than in the next two TDMA frames (information about the channel access requirements, such as maximum allowed interference level in different bands and channels, could be preconfigured or obtained from a higher layer entity).
2. Conduct measurements on the selected physical channel (in uplink slot and downlink slot) one TDMA frame before accessing the channel (this is necessary as the measurements which are used to make a decision could be outdated). If the measurement results indicate that the quality of the selected channel significantly degraded compared to the last conducted measurement, we select a new channel and repeat the procedure for the new channel
3. Access the channel in the slot allocated for uplink transmission (terminal-initiated connection) or downlink transmission (base station-initiated connection)



(a) selection of a channel which is accessible within next 2 frames

(b) conduct measurement to reassess channel quality in uplink and downlink slots (red circles)



(c) initiate transmission in the uplink slot

Figure 43: Example of a channel selection for terminal-initiated pilot bearer establishment (assuming 10 slots per frame and 10 frequency channels)

The message sequence chart for pilot bearer establishment is depicted in Figure 44 and requires exchange of two messages: Bearer Establish Request and Bearer Establish Response. The purpose of the Bearer Establish Request message is to inform the responding party about the intention of establishing a new bearer over the physical channel used for transmitting the request message (implicit reservation request). The purpose of the Bearer Establish Response is to confirm the successful reception of the Bearer Establish Request message and inform the initiating party about the availability of resources to handle a connection. If the Bearer Establish Request and Bearer Establish Response messages are followed with normal data transmission, the bearer is successfully established. In other cases (e.g. in case of a message error) the procedure fails and the channel selection procedure is repeated. In order to avoid collisions, a random backoff is performed before a new attempt.

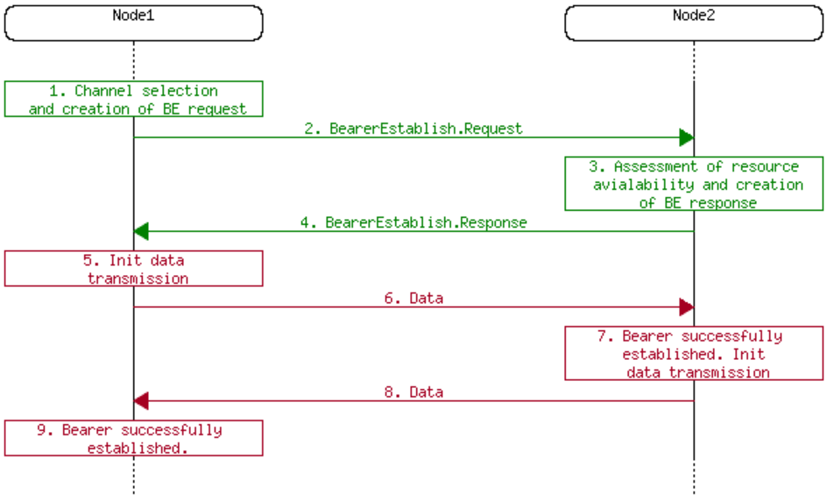


Figure 44: Message sequence chart for execution of pilot bearer establishment.

4.3.5.2 Non-pilot bearer establishment procedure

The procedure is used to establish non-pilot bearers (which are used for u-plane/data transmission) and overwrite pre-allocation of slots for uplink and downlink transmission thus allowing establishment of asymmetric bearers/links between terminals and base stations. The message sequence chart for non-pilot bearer establishment is depicted in Figure 45 below. In general, the procedure is used to 1) modify existing connections by establishing additional bearers, 2) establish a multi-bearer connection (during a connection setup or inter-cell handover), 3) reallocate resources for non-pilot bearers within the same cell (i.e. intra-cell handover). In contrast to the pilot bearer establishment procedure, the procedure allows the initiating party to modify channel scanning/hopping sequence of the receiving party, thus reducing the bearer establishment time. The procedure, similarly to the pilot bearer establishment procedure, is the same for the terminal-initiated and the base station-initiated bearer establishment and consists of two parts: channel selection and execution.

The channel selection part consists of four steps which can be described as follows:

1. Select the physical channel with the best quality (e.g. minimum level of interference) which does not breach any of the access requirements (information about the channel access requirements, such as maximum allowed interference level in different bands and channels, could be preconfigured or obtained from a higher layer entity).
2. Conduct measurements on the selected physical channel (in uplink slot and downlink slot) one TDMA frame before accessing the channel (this is necessary as the channel quality measurements which are used to make a decision could be outdated). If the measurement results indicate that the quality of selected channel significantly degraded compared to the last measurement, we select a new channel and repeat the procedure for a new channel
3. Inform the receiving party about physical channels selected for transmission to temporarily modify its scanning/hopping sequence (information can be conveyed over already established pilot bearer, or a pilot bearer which is being established). This step is optional and is used only if modification of scanning/hopping sequence is necessary.
4. Access the selected channel using the slot allocated for uplink transmission (terminal-initiated bi-directional bearer), downlink transmission (base station-initiated bi-directional bearer) or both slots (asymmetric bearer)

The procedure for execution of non-pilot bi-directional bearer establishment is similar to the procedure described in the previous section. The only difference is that the Bearer Establish Request can be preceded with a message exchange over a pilot bearer which temporarily modifies the scanning/hopping sequence of the responding party. In case of asymmetric (i.e. uni-directional) bearer, the message sequence is different and is presented below.

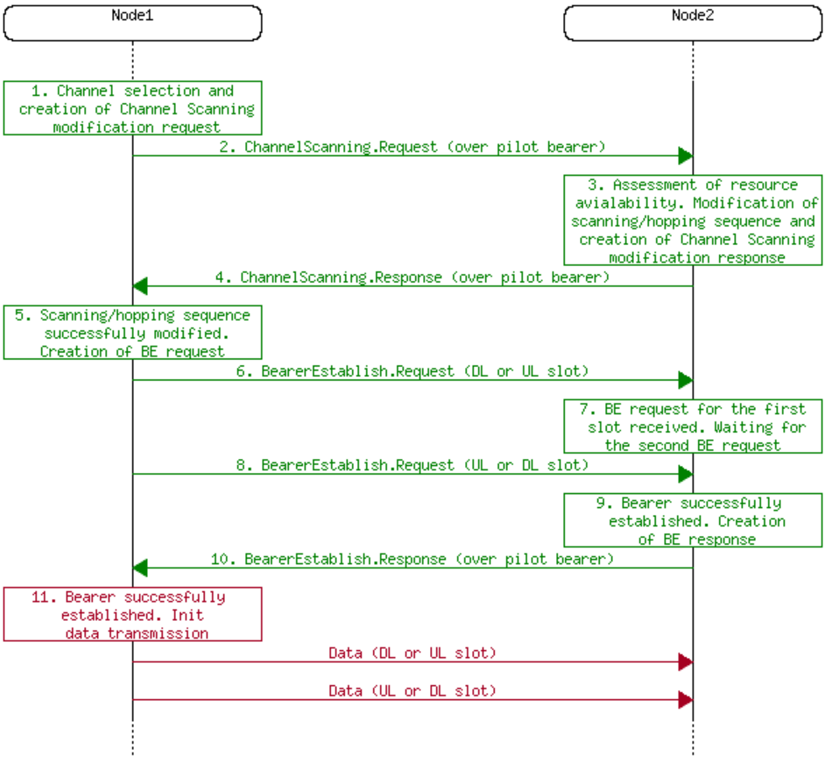


Figure 45: Message sequence chart for asymmetric bearer establishment.

4.3.5.3 Base station slot availability indication procedure

The procedure is triggered whenever a slot becomes unavailable (or available) for access. As mentioned earlier the BSs and terminals need to cease the scanning procedure for slots allocated to active bearers if there is sufficient number of transceivers to continue scanning. This leads to the "deafness problem" (also called the "missing/busy receiver problem"). In order to alleviate this problem, BSs broadcast information about slots which are unavailable for access (as terminals are expected to be accessed only by their serving base stations, terminals are not required to broadcast this information). In order to limit the overhead related with frequent slot status changes, the transmission of the updated information can be delayed to aggregate information about multiple slots. The message sequence chart for the slot availability indication procedure is shown in Figure 46 below.

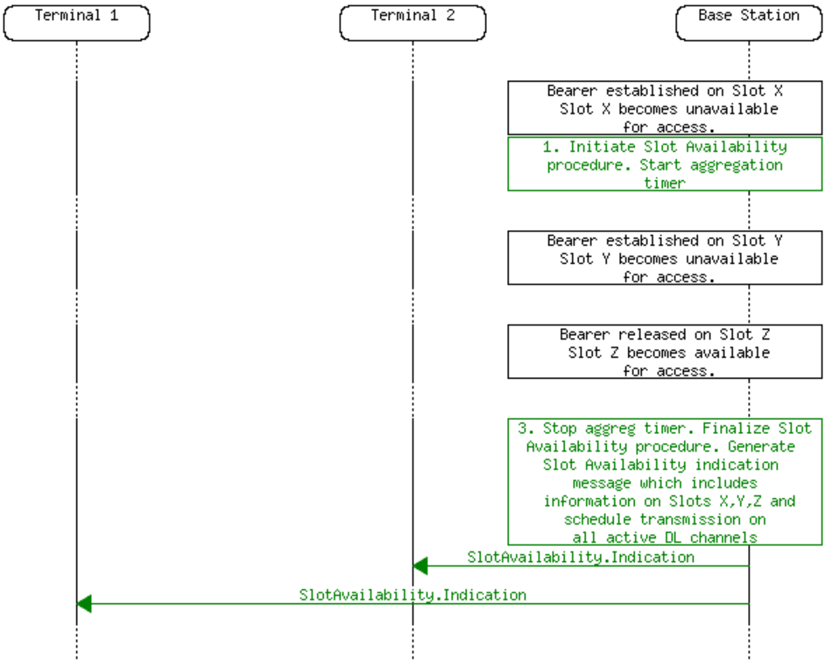


Figure 46: Slot availability indication procedure.

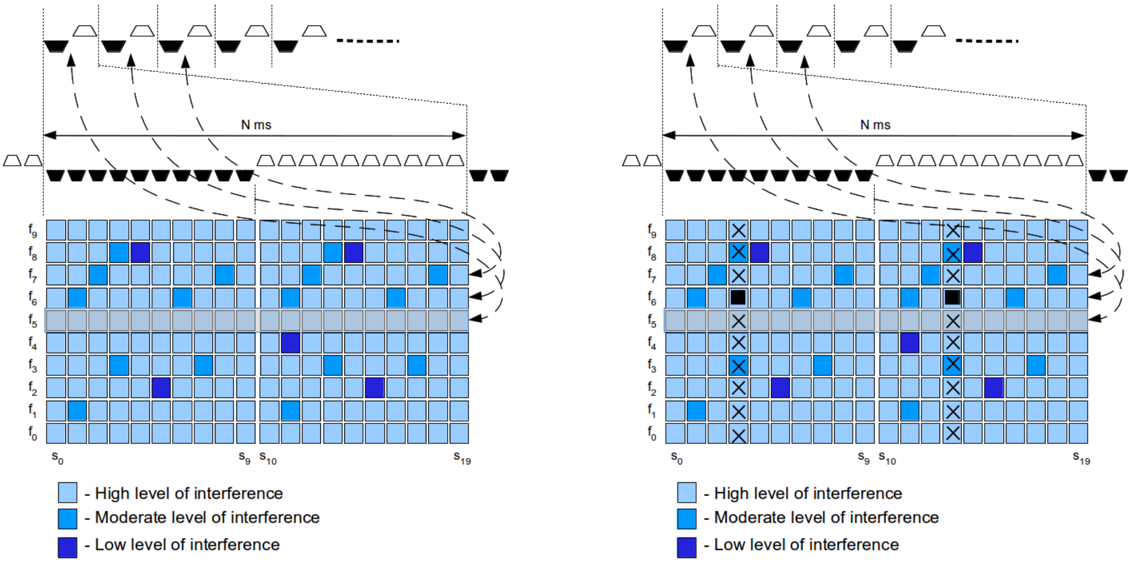
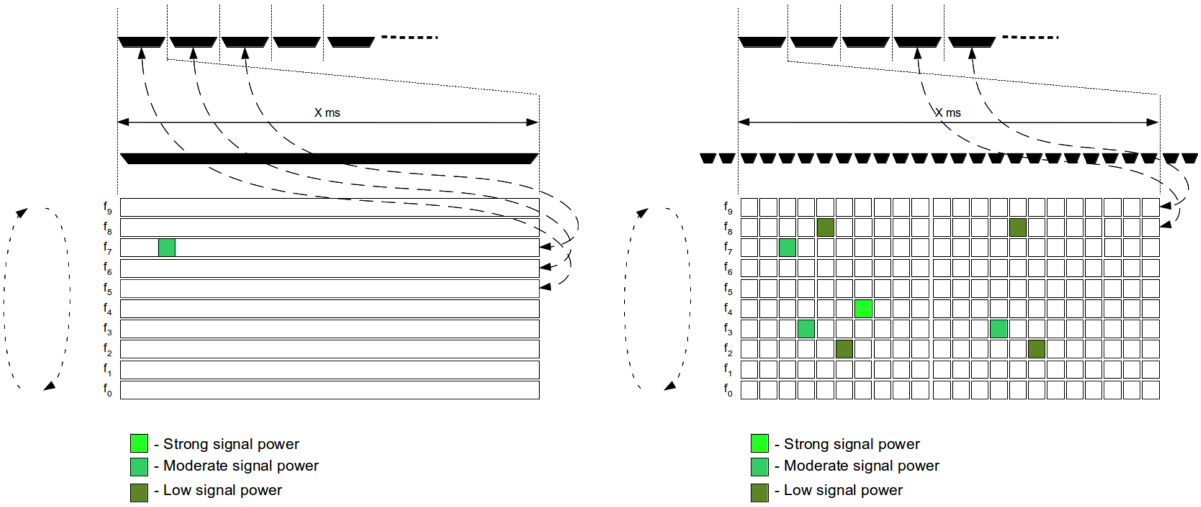


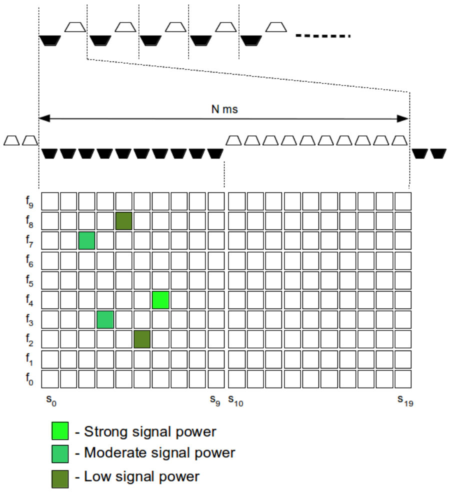
Figure 47: Impact of unavailable/blind slot on channel quality measurements and channel access in case of one transceiver (X – channels unavailable for access and quality measurements).

4.3.5.4 Terminal synchronization/locking procedure

The following section briefly describes the terminal synchronization/locking procedure. The procedure is triggered after a terminal is switched on. The main aim of the procedure is to allow terminals to establish slot and frame synchronization, find the closest base station and obtain all necessary information required to establish a connection with this base station. In general, the procedure consists of two phases. During the first phase (Figure 48(a)) the terminal scans for any receivable transmission with a base station identity which indicates that a given base station could be accessed by the terminal. When such transmission is received, the terminal obtains “slot synchronization” and moves to the second phase (it is worth to remind here that the base station identity is transmitted not only by base stations, but also by active terminals). During the second phase of synchronization/locking procedure (see Figure 48(b)), the terminal builds a map of all base stations available on different channels, while receiving information using the strongest detected downlink channel (in case a base station with a stronger signal is found, the terminal switches reception from one base station to another). When the terminal obtains frame synchronization it stops scanning physical channels pre-allocated for uplink (see Figure 48(c)). After obtaining all the necessary information, the terminal enters the “synchronized/locked state” and initiates association procedure to inform base station about its arrival.



(a)establish slot synchronization (b) build a map of available base stations



(c)establish frame synchronization

Figure 48: Terminal synchronization/locking procedure.

4.3.5.5 Base station synchronization/locking procedure

The following section briefly describes the base station synchronization/locking procedure. The procedure is triggered after a base station is switched on. The main aim of this procedure is to allow base stations to establish slot and frame synchronization with other base stations in the neighbourhood and to select a scanning/hopping sequence which minimizes the contention between terminals associated with different base stations. The procedure is also responsible for establishment a uni-directional broadcast channel for dissemination of common control information. It is worth noting here that the proposed MAC can still operate without the slot and the frame synchronization. However, the performance of such a setup would suffer from higher level of interference.

The procedure is similar to the “Terminal synchronization/locking procedure” and consists of two phases. During the first phase (see Figure 48, in the previous section) the base station scans for any receivable transmission with a base station identity. When such transmission is received, the base station obtains “slot synchronization” and moves to the second phase. During the second phase of procedure (see Figure 48(b)), the base station builds a map of all base stations available on different channels. When the base station obtains frame synchronization it stops scanning physical channels pre-allocated for uplink (see Figure 48(c)).Based on the observed scanning/hopping sequences in neighbouring base stations, the base station selects its own scanning/hopping sequence. After selecting its own scanning/hopping sequence, the base stations enters the “synchronized/locked state” and initiates a unidirectional broadcast channel for dissemination of common control information on a selected channel (the selection criteria may be different and may depend on the licensing regimes of different bands, or measured interference levels).

4.3.6 New Features in MAC design #3

4.3.6.1 Dynamic Channel Selection

As already mentioned, in contrast to the traditional cellular networks, it is foreseen that the UDNs will be in many cases installed without traditional RF planning and proper site selection. One of the main characteristics (and at the same time challenges) of the UDNs is therefore excessive inter-cell interference resulting from the inability to properly plan the network deployment. Additionally, as small cells are foreseen to operate in technology neutral bands, inter-system and inter-tier interference are also of a major concern. Finally, UDN deployments may experience significantly higher traffic load variability and traffic asymmetry variability compared to deployments with a high cell radius.

In order to address the mentioned challenges, the proposed MAC uses a dynamic decentralized procedure to select physical resources for transmission. This procedure is called the Dynamic Channel Selection (DCS) and builds on top of multi-channel operation and time-slotted access of the proposed MAC protocol. The procedure is “dynamic” in the sense that it allows terminals and base stations to change the allocation of physical resources on the per-frame basis and “decentralized” in the sense that it permits terminals and base stations to select physical channels for transmission without explicit MAC cooperation between nodes. To facilitate the DCS, the quality of available channels in terms of interference level is continuously monitored by terminals and base stations. This is possible as a result of TDMA/TDD frame structure (monitoring of the quality in the intervals between transmit and the receive timeslots) and channel scanning procedure which enables multi-channel operation (see previous section). Having information about the quality of available channels terminals and base stations can select appropriate resources for transmission. The selection based on the least interfered channel allows DCS for even distribution of interference over multiple channels thus minimizing the average probability of errors caused by interference. To address the potential problem of system instability resulting from the use of DCS (and at the same time maintain efficient resource utilization), different mechanisms can be used which are part of an ongoing study. The operation in different frequency bands requires the DCS operation to be tuned based on the regulatory requirements and information from Speed-5G cRRM or other radio interfaces (in case of multi-RAT devices). This is necessary to allow for a better inter-system coexistence and involves changes in the rules for channel selection (e.g. maximum interference level which permits channel access, minimum signal strength level of a detected radio system which permits access to a channel).

In general, the main aim of the DCS is to enable inter-cell and inter-system avoidance (by exploiting interference diversity) and thus eliminate the need for frequency planning. Additionally, the DCS allows the system to adapt itself to continuously changing traffic conditions by allocating resources on an “as-needed” basis. As a result, the DCS is considered to be a key feature of the proposed MAC design which enables efficient operation in dense (or ultra-dense) deployment across different bands.

4.3.6.2 Multi-RAT and multi-channel operation

The proposed MAC is capable to deal with more than one RAT simultaneously. For instance, the proposed MAC supports the possibility of exploiting another RAT (e.g. LTE) for transmission of common control information. This can potentially allow for faster distribution of information necessary for association with a base station and improved reliability in case of operation in highly loaded unlicensed frequency bands. In order to fully exploit the availability of resources available in multi-RAT devices, the proposed DCS-MAC supports heterogeneous resource aggregation. This means that it can be used in conjunction with other designs allowing for a cross-RAT spectrum/carrier aggregation. The proposed MAC is also designed to natively support operation in multiple channels (and bands) and thus aims at full exploitation of potentially available spectrum. In order to enable operation in multiple channels (and bands), each base station periodically scans all supported channels according to some predefined scanning/hopping sequence. The information about the scanning/hopping sequence is obtained by terminals during their synchronization with their respective base stations. This knowledge allows all synchronized terminals to determine which frequency channel (and when) will be scanned and initiate a transmission with their base stations. To enable a base station initiated transmission, terminals adapt a similar procedure and use a delayed version of the same hopping/scanning sequence as their serving base station. It is important to note that the proposed scheme allows for the allocation of new channels in the future as well as operation of terminals and base stations which support just a subset of available channels (and bands).

It needs to be highlighted here that the number of scanned frequency channels directly affects the delay of accessing a specific frequency channel, which in turn may affect the quality of service (the impact of this delay on the quality of service in different scenarios requires further investigation).However, this delay can be significantly reduced by employing additional transceivers which adapt a delayed version of the scanning/hopping sequence used by the first transceiver.

Another important fact worth highlighting is that, when using a single transceiver, BSs and terminals cease the scanning procedure for the duration of scheduled transmission or reception. This leads to the “deafness problem” (also called the “missing/busy receiver problem”). In order to alleviate this problem, BSs are required to broadcast information about physical channels which are unavailable for access. The problem can be also effectively handled by employing additional transceivers.

4.3.6.3 Dynamic UL/DL resource allocation

Due to the small size of deployed cells (and thus resulting from it a small number of users per cell), including an increasing popularity of the UL-heavy applications (e.g. social media, cloud based services), the traffic asymmetry in the UDNs may change rapidly within a single cell, or from one cell to another. In order to fully exploit the available resources, a network-wide allocation of resources for uplink and downlink may no longer be an option and radio systems will need to dynamically, rather than statically, allocate resources for uplink and downlink. This, in turn, means that cross-link (i.e. uplink-to-downlink) interference will be a major component of the inter-cell interference and thus will need to be properly addressed in the future mobile networks.

The proposed MAC protocol was designed to enable dynamic allocation of resources for UL and DL transmission. In order to address the problem of cross-link interference, the proposed MAC allows for fast re-selection of resources which suffer from excessive interference. The decision which resources to select is done by the DCS and it is made without explicit MAC layer cooperation between nodes. In order to prevent potential instability resulting from the decentralized nature of the DCS and maintain efficient resource allocation, different mechanisms are currently under investigation.

It is worth reminding here that the proposed MAC does not rely on time advancing to compensate for inter-slot interference. Instead, it shortens the transmission in each slot. Although this approach may seem less efficient, it actually enables flexible allocation of resources without a threat of cross-link inter-slot interference. The solution used in existing cellular standards such as TD-LTE or TD-

SCDMA involves allocation of a specific slot which eliminates such interference. The location of such slots is however static and reconfiguration of the frame structure is time consuming (thus limiting the flexibility and potential gains related to dynamic UL/DL resource allocation).

4.3.6.4 Decentralized decision making

Dense small cell networks are often envisioned to be inter-connected over a public network. This means that operators may not have control over the quality of the backhaul links of a large portion of their networks. Additionally, operators may often use non-ideal types of backhaul links, such as wireless links. As a result, operators may not always be able to maintain tight synchronization between different elements of their network which is necessary to support centralized interference coordination techniques, leading to the degradation of system performance (see e.g. [37]). Moreover, small cells are foreseen to operate in licensed as well as license-exempt bands, leading to inter-system and inter-operator interference. As a centralized interference coordination between operators in such a scenario may be signaling heavy and ineffective (existence of networks deployed by customers), other approaches may need to be used.

In order to address this issue, the proposed MAC aims at providing a decentralized solution for interference coordination in a form of the DCS mechanism. As mentioned, DCS is decentralized in the sense that physical channels for transmission can be selected by terminals or base stations and does not require any explicit MAC layer cooperation between nodes. One of the main advantages of such decentralization is the reduction in signaling overhead on the air interface and in the backhaul. Additional advantage is related with better resistance against interference which stems from the fact that channel (re-)selection does not require terminals to communicate with base stations. This can be clearly seen in case of inter-cell handovers which does not rely on the successful exchange of control information with the source base station prior the handover. Whilst in a typical macro-cell network this is not usually an issue, exchange of such information may be problematic in case of dense small cell networks which can be characterized by high inter-cell interference resulting from the poor frequency planning. Similar problems may also appear in technology neutral bands, where different radio systems can be deployed or shared bands in which proper planning is not feasible.

It is worth highlighting here that the number of terminals in dense (and ultra-dense) networks served per base station is foreseen to be very small [40]. This means that the benefits of base station oriented resource allocation (e.g. exploiting user diversity) may be marginal or may completely disappear in case the number of base stations exceeds the number of users. This phenomenon is further amplified by the dominance of Line-Of-Sight (LOS) propagation in dense deployments resulting for short inter-site distances. This means that the channel conditions for different users in a cell may be highly correlated. In such conditions allowing terminals to actively participate in resource allocation could provide significant benefits in terms of reduction of signaling overhead over the air interface and exploitation of base station diversity.

An important issue related with the use of decentralized solutions for interference coordination is the threat of system instability which may lead to degradation of system performance and increase in signalling overhead caused by continuous reallocation of resources. In order to prevent this from happening different mechanisms could be used which are a topic of an ongoing study.

4.3.6.5 Support for cluster based architecture and Handovers

As presented in (see e.g. [33]), the small radius of cells in UDNs may lead to an exponential growth in mobility related signalling and handover failures caused by handover delay and/or lengthy cell discovery (some terminals may lose their connectivity with a new cell before the ongoing handover procedure is completed). Additionally, due to insufficient capacity, macro-cells in the near feature may no longer be able to handle traffic of fast moving users (which is a common practice in existing networks). This means that traffic of fast users would need to be handled by small cells, thus further increasing the number of handovers.

In order to mitigate these problems, new mobility management procedures are necessary which enable fast, light and efficient handovers of terminals between cells in the UDN. The existing proposals which intend to address these problems are mainly based on the separation of control and user planes to offload mobility related signaling to overlay macro-cell networks [34]. Additionally, the proposals suggest using the overlay macro-cell networks for assisting terminals in discovering neighbouring cells. Due to different circumstances (e.g. unavailability of the overlay network, poor assistance in discovering neighbouring base stations in the indoor environment), the application of these proposals may be limited and alternative methods for handling mobility in UDNs are necessary [38].

In order to address these issues, the proposed MAC supports terminal controlled handovers and cluster based architecture with fast L1/L2 handovers within clusters. The introduction of terminal controlled handovers is facilitated by the proposed RACH design which is based on flexible multiple access and allows for faster handovers and improved resistance to interferences. This is possible as terminal controlled handovers do not rely on the exchange of information with the source base station but with the target base station. Additionally, terminal controlled handovers decrease the control traffic towards the core network by limiting the amount of signaling which needs to be exchanged between a source base station and a target base station.

The handover in the proposed MAC is referred to as “L1/L2 handover” since it uses procedures which are essentially the same as the procedures used for reallocation of resources for an existing bearer in a cell. This stands in a sharp contrast with existing cellular systems which require dedicated RACH procedures to precede the actual handover. The use of the same procedures for reallocation of resources for a bearer in a cell and a handover means that handovers in the proposed MAC can be subdivided into inter-cell handovers and intra-cell handovers. The intra-cell handover happens when a new channel is selected by the DCS for an existing bearer in the same cell.

As a result of using a non-continuous TDMA, each transmission in the proposed MAC carries sufficient information enabling successful decoding and demodulation by a receiver. This allows faster and more robust discovery of new cells and better resistance to accidental or malicious interference of common control channels. Additionally, the use of a non-continuous TDMA allows for the support of seamless inter-cell handovers and thus exploitation of base station diversity.

The cluster based architecture in the proposed MAC is facilitated by splitting MAC functionalities into the lower-MAC, located in the cluster member, and the high/upper MAC, located in the cluster controller. Based on this split, the lower-MAC is responsible for management of radio bearers (e.g. monitoring their quality and triggering handover, if necessary) and monitoring the quality of other channels as well as handling new incoming connections. The higher-MAC is left then with controlling of broadcast information and handling L1/L2 handovers.

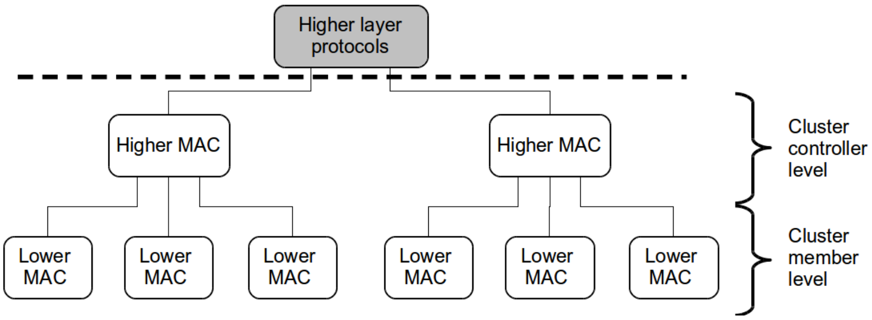


Figure 49: Functional split for higher and lower-MAC and its location.

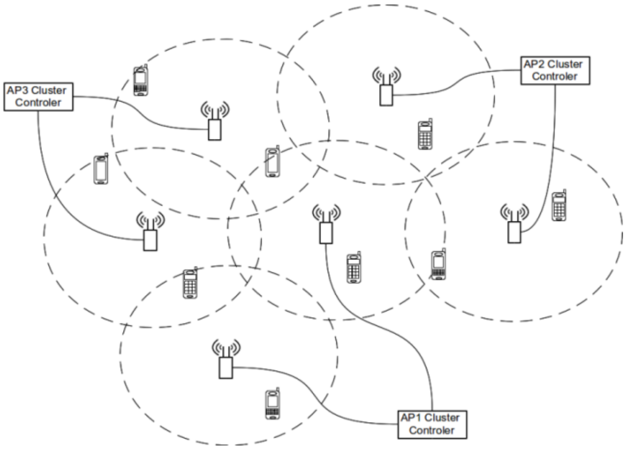


Figure 50: Cluster based architecture for the proposed MAC

4.4 Summary

This chapter presented the design of MAC functions, which makeup the eDSA capable MAC framework of SPEED-5G. More specifically, the framework supports the management of RATs for carrier aggregation as depicted in chapter 3, as enabler for capacity maximization and interference management. Three distinct MAC designs have been presented and described.

The first MAC design which assumes a FBMC PHY, supports a channel access scheme which exploits the FBMC characteristics. It has been designed to allow the offload of broadband and/or IoT traffic on unlicensed bands (respectively 5 GHz and 868 MHz bands), being used as secondary carriers or not. This MAC is able in both cases to adapt the frame configuration, according to coexistence decisions or to the traffic types which are offloaded.

The second MAC design extends the LAA concept of LTE by supporting multi-RAT carrier and spectrum aggregation for dense heterogeneous networks covering broadband and IoT traffic types. NOMA concept as well as energy efficiency by means of applying the DRX operation to control planes are integrated in this design.

The third MAC design supports the cases where the SC cannot rely on a connection with the virtualized architecture where the centralized RRM is located. In this situation, the MAC layer doesn’t get any configuration from RRM however the new design is able to deal with the interference levels characteristic of ultra-dense deployments.

The interface between MAC and cRRM will be further refined to make it amenable to implementation in task T5.3.

5 MAC evaluation

This section introduces the system-level simulation scenarios, parameters and analysis of the evaluation results, of the MAC designs described in section 4. For each MAC design, the simulation assumptions (e.g., parameters, layouts, models of traffic, performance metrics etc.), analysis and conclusions are presented, on an individual basis. The main aim in this section is to present simulations results and analysis used to validate the specific features of each MAC design on selected scenarios (as an illustration, performance results of the IoT flavour of design #1 and first evaluation of the DCS-MAC for broadband perspective are given). **A more rigorous comparison of various designs based on common scenarios and simulation assumptions, together with assessment of delays and overheads will be provided in future deliverables/reports (see section 5.4).**

5.1 Mac Design #1b: IoT UL/DL offload on shared spectrum

This section reports on the simulation of MAC protocol for offloading IoT traffic on 868 MHz band, as described in section 4.1.3. The proposed MAC design has been implemented on a system-level simulator called WSNet, which is an event-driven system level simulator initially developed to model and evaluate protocols (MAC layers and above) for large scale wireless network. The interested reader can refer to the WSNet website[5], to get details on this simulation tool. This subsection describes the evaluation methodology, namely detailing the network parameter, layout and models that have been chosen.

The deployment scenario considered in this simulation is an indoor scenario. The main purpose of this simulation is to investigate the amount of IoT traffic that can be offloaded on to shared spectrum, using the SPEED-5G MAC layer based on FBMC PHY, with respect to interference context. We consider a virtual office layout scenario (shown on Figure 51) derived from the "Virtual Office" scenario presented in [23] and considered as a baseline of this simulation.

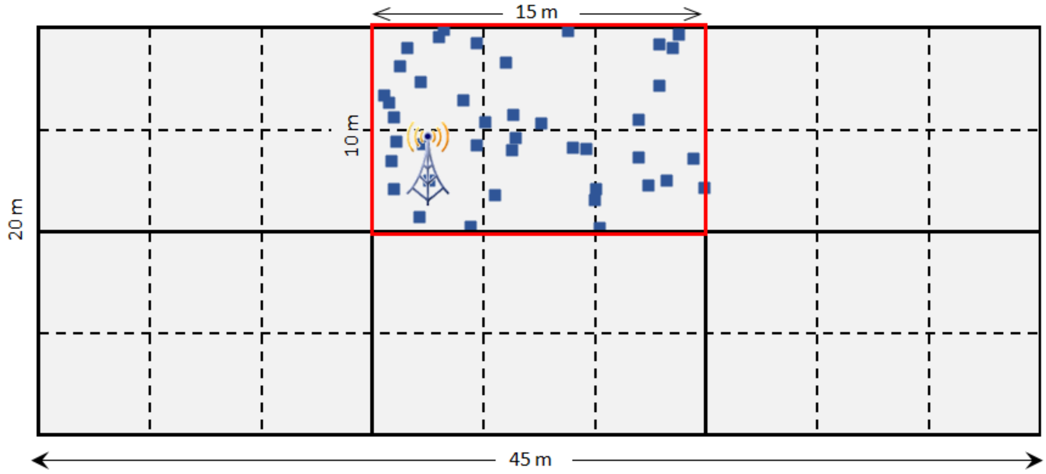


Figure 51: Virtual home layout

5.1.1 Scenario-specific simulation assumptions and parameters

The home indoor deployment scenario shown in Figure 51 has been extended, considering a building having a total area of 45 m by 20 m. In particular, the building consists of several apartments of area 15 m by 10 m, each composed of 6 rooms. In this baseline scenario, we consider one SC per

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[5] http://wsnet.gforge.inria.fr/index.html

apartment composed of a base station and N IoT devices (being either sensors or actuators), whose distances from the small cell (SC) station are uniformly randomly distributed. The results are provided for one small cell (one apartment) taking into account the interference from neighbour small cells. Figure 52 illustrates an example of such indoor scenario composed of 6 small cells, where 200 devices per small cell are randomly dropped in the total area of 45 m by 20 m. The small cell of interest is highlighted by a red rectangle.

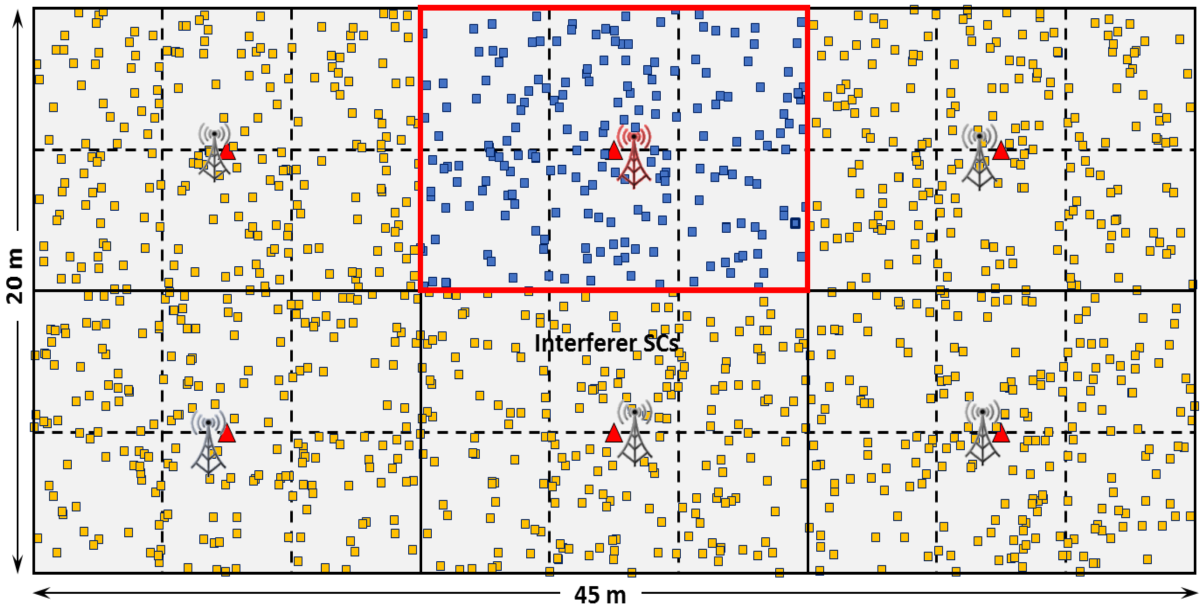


Figure 52: Example of indoor home Scenario

Table 18 gives the simulation parameters in terms of network layout, models and set-up, which are partly taken out of [14] and [26]. All the devices of the small cell of interest compete to utilize a shared frequency band of 3 MHz. This spectrum is divided into 12 sub-channels of 180 KHz each and the beacon sent by the small cell spans over the entire band. To model the interference, we randomly drop in the adjacent apartments a number of devices which send periodic reports using the same channel as the devices in the SC of interest. We further assume that the beacons from different SCs are sent in disjoint periods (no collision between beacons). In order to balance the link budget between uplink and downlink transmissions, the transmit power of the device is reduced to 0 dBm and the antenna gain of the small cell is set to 0 dBi corresponding to one antenna configuration at the transmission and reception ($N_{Tx} = 1\ , N_{Rx} = 1$).

Table 18: Main simulation parameters

simulation parameters	Value
Layout	One small cell per apartment, 5 interfering apartments and one apartment of interest.
Frequency band Bandwidth Number of sub-bands Sub-band bandwidth	868 MHz 3 MHz [865-868] 12 180 kHz
Distance-depth path loss model	Mix of ITU InH [referring to Table B.1.2.1-1 in [14][26] LoS $L_P = \ 82.27 + 16.9\log_{10}(d)$ (d km, f = 868 MHz) NLoS $L_P = 120.60 + 37.6\log_{10}(d)$

simulation parameters	Value
	NLoS2 $L_P = 140.17 + 43.3\log_{10}(d)$
Penetration loss (Only internal wall penetration loss is considered	$= \mathrm{Wi} * \mathrm{p}$ Wi = the loss in internal walls = [4-10] dB uniformly distributed p = the number of penetrated internal walls (0 - 3)
Propagation channel model	TU (ITU InH)
Doppler spread (Mobility)	1 Hz (Stationary IoT devices, speed = 0 km/h)
Shadowing std. Deviation	Los (3 dB), NLoS (4dB), NLoS2 (8dB)
Interference/noise	Sensitivity (baseline model) Interference model: drop a large number of devices in adjacent small cell to generate period traffic that interferes with the traffic of the small cell of interest.
Antenna configuration Antenna Pattern	SC: $N_{Tx} = 1$, $N_{Rx} = 1$ IoT device: $N_{Tx} = 1$, $N_{Rx} = 1$ 2D Omni-directional (baseline)
BS Noise Figure	3 dB
UE Noise Figure	5 dB
Thermal Noise Figure	-174 dBm/Hz
Rx Antenna gain of BS + connector loss	0 dBi
Rx Antenna gain of UE	0 dBi
Number of UEs	$N = 200$ UEs per small cell
UE dropping for each apartment	All UEs randomly dropped and within coverage of the small cell in the unlicensed band
Traffic model	Uplink traffic produced by low end IoT devices sending periodic reports in uplink traffic. DL/UP traffic produced by sensors/actuators (NCs and responses to NC).

In terms of traffic patterns, 3 different scenarios have been considered with different types of devices and traffics which are reported in *Table 19*. It is worth noting that although a bidirectional communication is assumed, the UL communication from an end device to the base station is expected to be the predominant traffic.

Table 19: Scenarios of IoT traffic

Scenario	Description
# 1	UP traffic in CAP : - 100 % of devices Case 1 : no ACKs

	Case 2: 100 % ACKs	
# 2	UP traffic in CAP and CFP: - 80 % of devices (CAP) - 20 % of devices (CFP) – 3 priority levels for RREQ - 50 % ACKs	
# 3	UP and DL traffic in CAP and CFP: - 80 % UP traffic (80 % CAP, 20 % CFP) - 20 % DL traffic (NCs) - 50 % ACKs - 50 % Response to NCs	NC: Basic mode Latency (NC) : - 5 % < 1s - 10 % < 1min - 25 % < 5min - 50 %< 10min

In the first scenario, uplink traffic in the CAP is considered with a reporting interval of 15 minutes. Different cases are studied in this scenario. In the first case, no acknowledgment is required, while in the second case, an acknowledgment is required with a maximum number of retransmissions equal to 2.

In scenario 2, uplink traffic is investigated in both CAP and CFP. Since, the number of devices that required dedicated resources for sending their reports is generally limited; the split of devices is assumed 80 % in the CAP and 20 % in the CFP. The device sends therefore a reservation request (RREQ) in the CAP; the small cell, based on the request and resource availability, schedules the transmission in next superframe and notifies the device about the scheduled resource in the beacon. If there is no notification, the device resends the request with a high level of priority. 3 levels of priority are considered in the simulation. In addition, the assumption is made that 50 % of devices require an acknowledgment.

Scenario 3 is a more realistic scenario in which uplink and downlink traffics are investigated. In this scenario, the traffic patterns derived from 3GPP cellular-IoT are considered. In this traffic model, 80 % of devices perform periodic reporting with only 50 % require an acknowledgment. Meanwhile 20 % of devices are able to receive network command from the SC, and only 50 % of these devices send a response to the command within a specified latency. For network command functionality, the basic mode is considered in which the SC repeats NC notification in the beacon over a period longer than the device wake-up period. The latency to response to NC may vary from 1 sec to 10 min. The split of NC devices with respect to latency is as follows: 5 % < 1 s, 10 % <1 min, 20 % < 5 min and 50 % < 10 min. The periodic reports and the responses to NC are assumed to be 100 Bytes payload length, while NC packets are short packets of 20 Bytes. ACK packets are sent via a broadcast acknowledgment and have variable payload length depending on the number of devices that must be acknowledged.

For the different traffic patterns, the following performance metrics are considered for the evaluation of MAC protocol: latency, packet delivery ratio (percentage of the transmitted packets) or percentage of dropped packets, average number of packet retransmissions, power consumption. The latency for UL periodic reporting is evaluated, as specified in [14], by including the time for device to synchronize to the network and the time for an access attempt from the device till the time to successfully receive the UL application layer payload at the SC. The capacity metric is defined as spectral efficiency in number of reports/hour. Low power consumption of devices is required to enable long battery life. The devices may have a battery life ranging from hours to 10 years. The purpose of energy consumption analysis is to calculate the achievable battery life for an IoT device using a specific candidate solution. A 5Wh battery capacity shall be assumed, without consideration of battery leakage impact since this depends on battery technology.

5.1.2 Simulation results and analysis

The following sections provide the simulation results for the 3 considered traffic scenarios. The performance of the network in terms of latency, percentage of packet loss and percentage of packet retry has been evaluated by simulation. For downlink traffic, an analysis of energy consumption is also considered. The influence of important effects on the performance like the number of active sub-channels (sub-carriers), the traffic density and the CAP length has been studied. In this regard, *Table 20* shows other specific assumptions relevant for the simulations like the number of available sub-channels, the length of the contention access period, the interference margin (able to model the noise floor in the shared spectrum due to a varying electromagnetic pollution of the 868 MHz band by other coexisting systems).

Table 20: Additional Simulation assumptions

Parameter	Value
Reporting interval (RI)	15 min
Contention access period (CAP) length	[32-64-128-256] slots
Number of available sub-channels	[1-3-6-9-12]
Interference margin	[20-30-40-50] dB
Traffic density (reports/h) in total area Traffic density per small cell (traffic of interest) Equivalent number of devices /small cell	[4,800-192,000] reports / h [800-32,000] reports / h [200 – 8000] devices with RI = 15 min
Packet payload size	MAR, Response NC: 100 Bytes NC: 20 Bytes
Acknowledgement policy	No Ack or Ack
Max number of retransmissions (in case of Nacks)	2
Duration of simulation	24h (86400s)

5.1.2.1 Scenario 1: UP traffic in CAP

In this scenario, uplink traffic in the CAP is extensively analysed with and without acknowledgment. The latency for periodic report is first evaluated. This latency includes time to synchronize to the network, time for random access and time to transfer the message. In case of no acknowledgment, the results show that increasing traffic density slightly increases the latency for sending the reports with one sub-channel, while the latency with 12 sub-channels is not affected. This latency has been shown to be below 600 ms for 90th percentile of reports. This is because no acknowledgment is required; therefore, the latency of sending packets is limited by the time to access the channel. The maximum allowed number of random access attempts for each periodic report is set to 2. After 2 failed attempts, the device drops the packet without effectively sending it. We refer to this case as packet loss due to no channel access.

Figure 53.a and Figure 53.b show the cumulative distributed function (CDF) of the SINR per report with one and 12 sub-channels, respectively. The SINR values of successfully received packets are only considered in CDF. The value in the parenthesis corresponds to the equivalent number of devices that can be supported. In case of one sub-channel, the SINR is higher when the traffic density is lower with up to 10 dB and 20 dB for 40th and 20th percentile of reports, respectively. The degradation of SINR value is due to the increase of interference between packets. Meanwhile, the SINR is not impacted with a large number of available sub-channels.

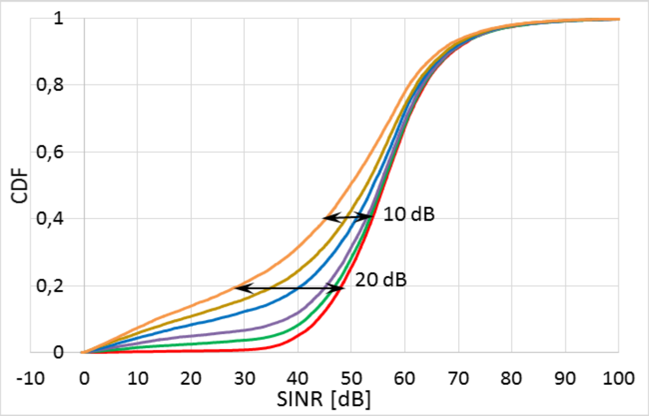


*Figure 53.a - CDF of SINR for periodic reports; one sub-channel is assumed available, **No-ack**.*

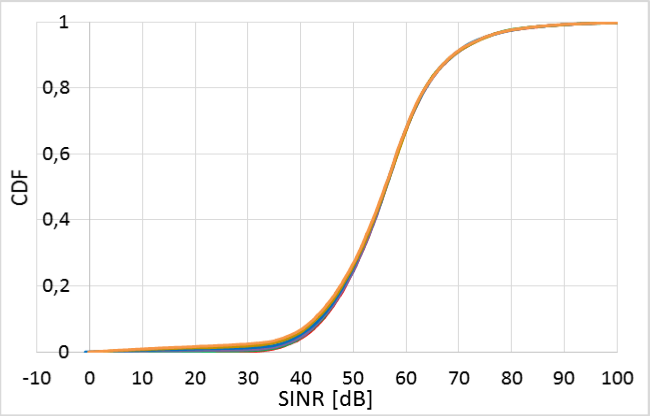


*Figure 53.b - CDF of SINR for periodic reports; 12 sub-channels are assumed available, **No-ack**.*

In *Figure 54*.a and *Figure 54*.b, the percentage of packet loss is illustrated. The packets may be dropped either due to interference from other packets, the SC receives the packet but it is not able to decode it due to low SINR value “SINR drop”, or because the device drops the packet without sending after when reaching the maximum number of random access attempts “No access”. As can be seen, the percentage of packet loss increases significantly with traffic density in case of one available sub-channel up to 36 % with 8000 devices (SINR Drop = 21 %, No access = 15 %). It can be also noticeable that the increase of packet loss is due to congestion resulting from the high data traffic load “no channel access”. For example, with N= 8000 devices, packet loss = 25 % (SINR drop = 19.3 %, No access = 5.6 %), while with N= 8000 devices, packet loss = 36 % (SINR drop = 21 %, No access = 15 %). This reveals that packet loss due to SINR become nearly constant and increases significantly to no access. In case of 12 available sub-channels, there is no loss due to channel access; the packets are dropped due to SINR with up to 3.5 % with 8000 devices.

Figure 55.a shows the impact of increasing the number of available sub-channels on packet loss with a traffic density of 120,000 reports/h. It is clear that the percentage of packet loss decreases significantly from 20 % to 8 % with 3 sub-channels and to 4 % with 6 sub-channels. The main cause of packet loss is the low value of SINR. Indeed, with 3 sub-channels, all devices experience a successful access to the medium and sent their reports. This can be also seen in *Figure 55*.b, where the SINR of reports is improved with 3 sub-channels by 10dB compare to 1 sub-channel due to the repartition of packets across multiple sub-channels, which subsequently reduces the probability of interference and collision between reports on each sub-channel. It should be noted that the impact of CAP length has been also investigated. The results show that there is no significant impact on the latency and packet loss in the scenario with no acknowledgment.

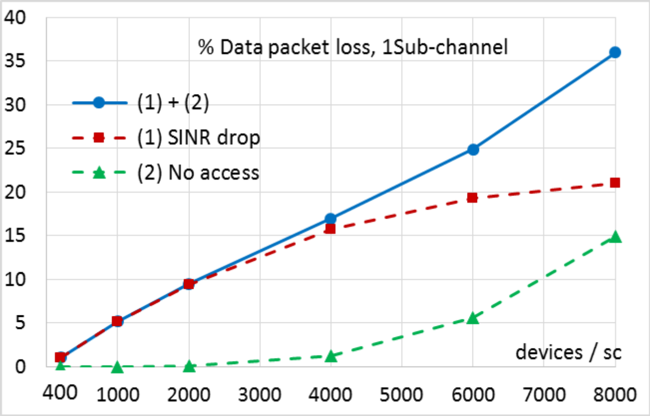


*Figure 54.a: Percentage of packet loss in function of the number of devices (1 Sub-channel), **No-ack**.*

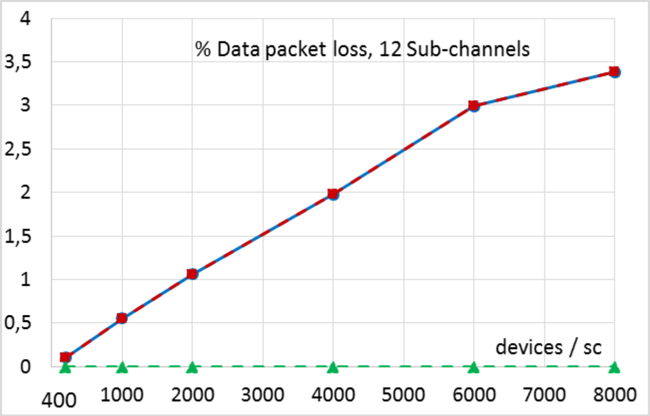


*Figure 54.b: Percentage of packet loss in function of the number of devices (12 Sub-channels), **No-ack**.*

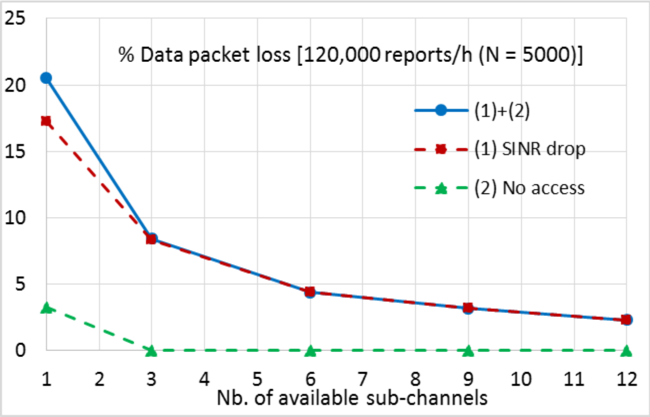


*Figure 55.a: Percentage of packet loss in function of the number of available sub-channels (N= 5000), **No-ack**.*

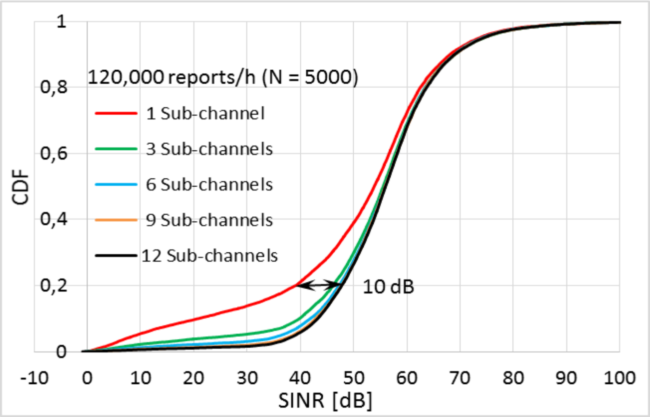


*Figure 55.b: CDF of SINR for periodic report; with variable number of available sub-channels (N= 5000), **No-ack**.*

In previous simulations, no acknowledgement policy for periodic reports is used. However, it is worth to view the impact of the acknowledgement on the performance. In a similar way, *Figure 56*.a and *Figure 56*.b shows the CDF of achieved latency for periodic reports requiring an acknowledgment with 1 sub-channel and with 12 sub-channels, respectively. As can be seen, increasing the traffic density in case of 1 sub-channel inevitably increases the latency for sending reports due to packet retransmission. However, this increase is less significant with a large number of available sub-channels (12 sub-channels). Comparing the latency with and without acknowledgement, it can be notice that the latency is higher in case of acknowledgment with one active sub-channel. As for the SINR in *Figure 57*.a and *Figure 57*.b, the SINR is improved by 28 dB with low traffic density for 20th percentile of reports. This is mainly due to the reduction of report interference levels.

To further view the impact of traffic density, the percentages of packet loss and of packet retries are shown in *Figure 58* and *Figure 59*, respectively. Packet loss resulting either from unsuccessful access to the channel or from SINR drop is presented. If the packet is sent at least one, with unsuccessful access after 1 retry or 2 retries, the packet is considered dropped due to SINR. As can be seen, the percentage of packet loss (only due to SINR) can be neglected in case of 12 sub-channels (< 0.05 %). However, this percentage increases significantly in case of 1 sub-channel up to 32 % with 8000 devices (corresponding to a traffic density of 192,000 reports/h). This percentage is small (<1 %) with 2000 devices/sc. It is hence concluded that the small cell with one sub-channel is able to support up to 2000 devices without any, or very limited, performance degradation. We can also notice that the packet is mainly due to the inability of the device to send it, because the channel has been found busy “No access”.

Comparing the total packet loss without and with acknowledgment, we can see that there is only 4 % of improvement in case of Ack with high traffic density (8000 devices) despite the high percentage of retry, this is mainly due to the high level of network congestion and to unsuccessful channel access attempt to send packet. Indeed, the percentage of packet loss resulting from “No access” in case of acknowledgment is 10 % higher than the case when no acknowledgement is required. If the device does not receive an acknowledgment for a given packet, it content to send the packet again. The retransmission of packets effectively increases the traffic load in the network and causes more congestion and subsequently more packet loss.

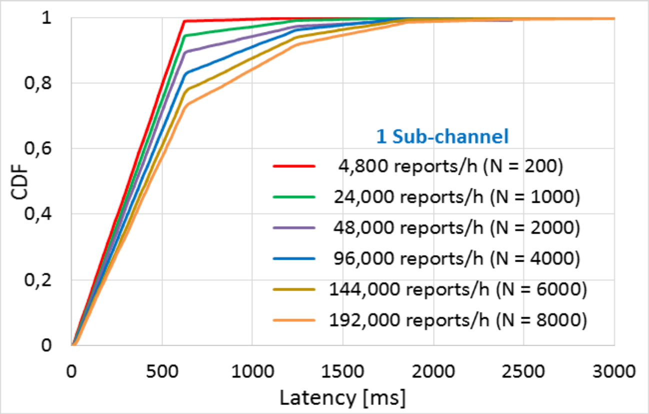


*Figure 56.a: CDF of latency for periodic reports; one sub-channel is assumed available, **ack.***

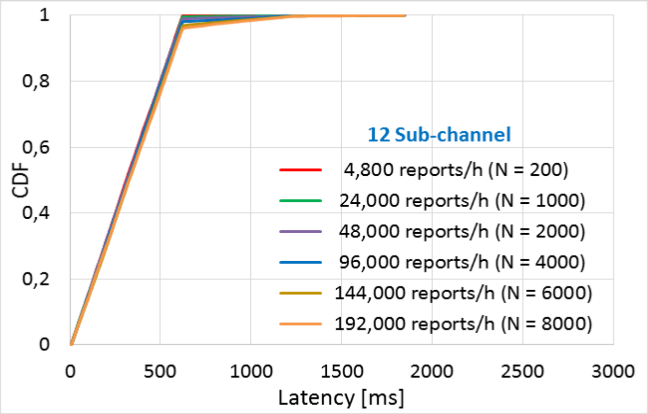


*Figure 56.b: CDF of latency for periodic reports; 12 sub-channels are assumed available, **ack.***

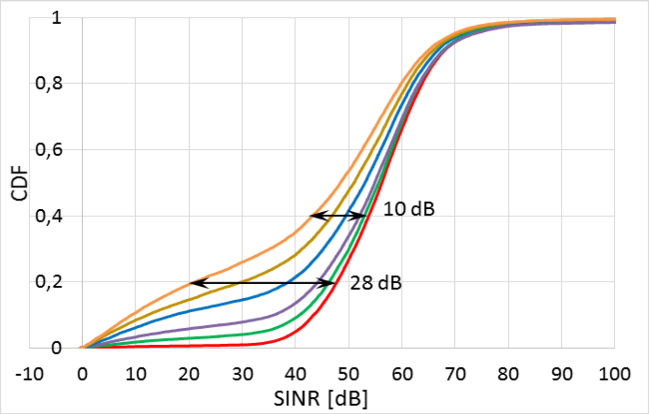


*Figure 57.a: CDF of SINR for periodic report; one sub-channel is assumed available, **ack.***

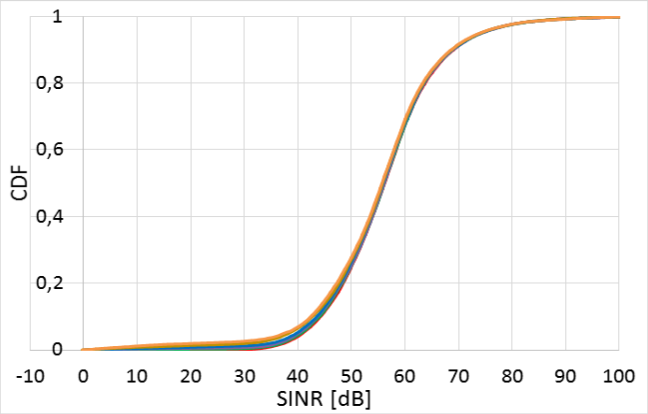


*Figure 57.b: CDF of SINR for periodic report; 12 sub-channels are assumed available, **ack.***

For packet retry in *Figure 59*, the percentage of 1 retry and 2 retry are distinguished as well as the percentage of total packet retry. Similarly, the percentage of packet retry increases with the number of devices up to 25 % in case of 1 sub-channel and 4 % in case of 12 sub-channels. The percentage of 2 retry is less than the percentage of 1 retry in both cases. This percentage is less than 0.4 % in case of 12 sub-channels. However, with 1 sub-channel, the percentage of 2 retry is much significant (8 %). It is clear that this retransmission has a visible impact on the latency as has been shown in *Figure 56*.

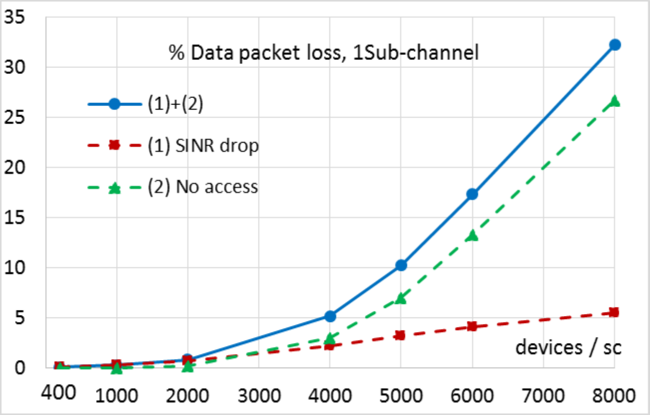


*Figure 58.a: Percentage of packet loss in function of the number of devices (1 Sub-channel), **ack.***

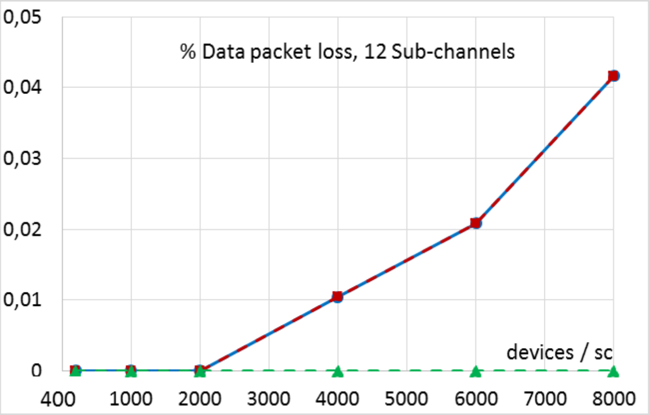


*Figure 58.b: Percentage of packet loss in function of the number of devices (12 Sub-channels), **ack.***

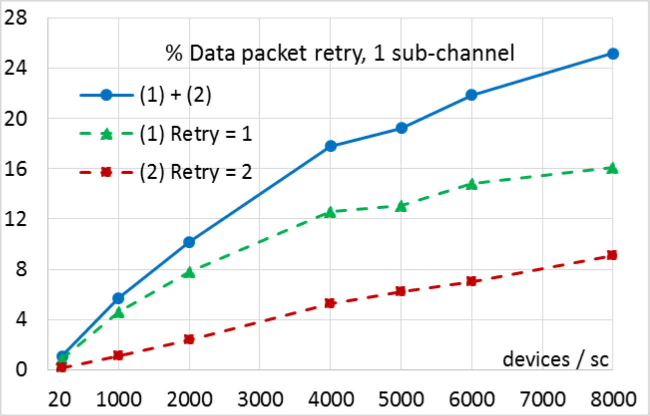


*Figure 59.a: Percentage of packet retry in function of the number of devices (1 Sub-channel), **ack.***

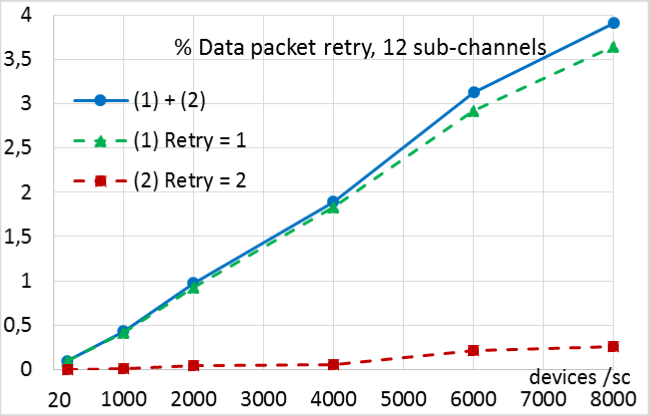


*Figure 59.b: Percentage of packet retry in function of the number of devices (12 Sub-channels), **ack.***

It is also important to evaluate the impact of the number of available sub-channels and the CAP length on the performance. For this purpose, the traffic density of 120,000 reports/ h (N = 5000 devices /sc) is considered, in which the percentage of packet loss is around 10 % (10.23 %).

The CDF of the latency and the SINR with respect to variable number of sub-channels are presented in *Figure 60* and *Figure 61*, respectively. In addition, the packet loss and packet retry percentages are depicted in *Figure 62* and *Figure 63*, respectively. From these Figures, it can be clearly seen that by increasing the number of available sub-channels, the latency is reduced, the SINR is improved, the percentage of packet loss and packet retry are decreased. In particular, with 3 sub-channels, the performance of the system is acceptable and the impact on the previous metrics is very small (packet loss = 0.35 %, packet retry = %). Even with 2 sub-channels, the percentage of packet loss decreases significantly from 10 % to 1.2 % and the percentage of packet retry decreases from 20 % to 12%. This is because increasing the number of available sub-channels will subsequently decreases the probability of collision as well as the delay to get a random access to the channel. The number of available sub-channels can be therefore adjustable with respect to the traffic load and the level of interference.

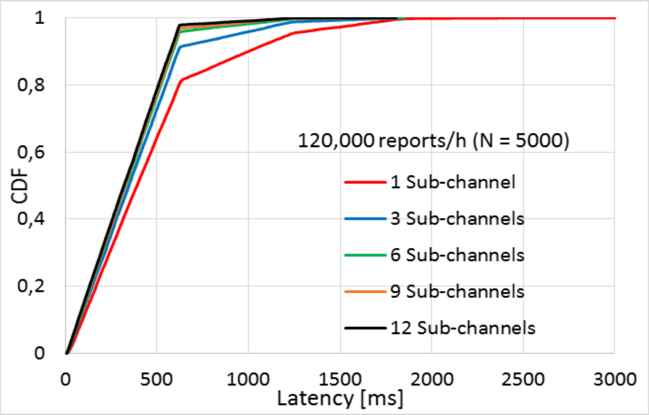


*Figure 60: CDF of latency for periodic reports; variable number of available sub-channels, **ack.***

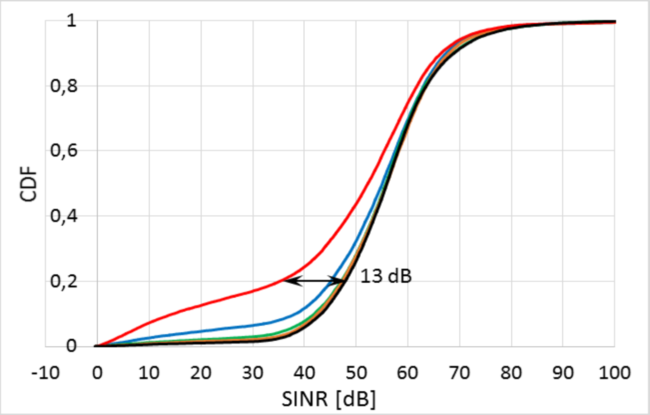


*Figure 61 : CDF of SINR for periodic reports; variable number of available sub-channels, **ack.***

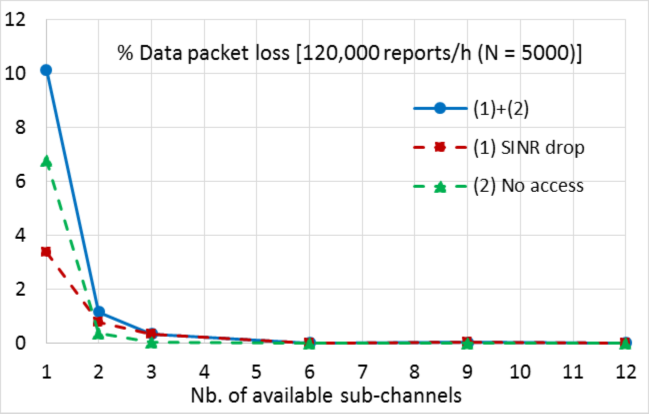


*Figure 62 : Percentage of packet loss in function of the number of available sub-channels, **ack.***

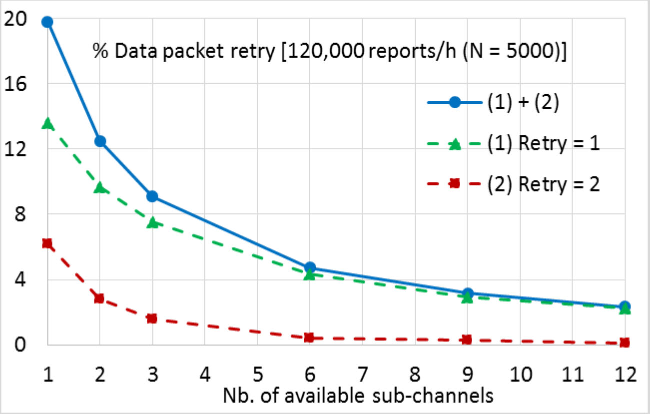


*Figure 63 : Percentage of packet retry in function of the number of available sub-channels, **ack.***

The impact of CAP length on the performance has been also investigated for a traffic density of 120,000 reports/ h (N = 5000) with 1 sub-channel. The obtained results show no impact on the latency, the SINR of periodic reports and the percentage of packer retry. The impact on the packet loss is presented in *Figure 64*. As can be seen, there is a no significant decrease of packet loss (only 2 %) when increasing the CAP length from 32 to 64 slots. This is explicated by the maximum number of random access attempts allowed to send the packet. If after 2 failed access, the device doesn't find an idle channel to send the packet, the packet is dropped. Therefore, increasing the CAP length will have no effect if the packet is dropped. In order to better illustrate the impact of CAP length, the maximum number of channel access attempts is set to 3 before dropping packets. In this case, it can be seen that the percentage of packet loss (*Figure 65*) decreases from 9 % to 3.5 % with CAP = 64 and remains constant with larger CAP length. The percentage of packet retry is not affected since the probability of collision and to access one channel will be similar.

Note that the CAP length is an important parameter that can be dynamically adjustable by the small cell depending on the traffic density.

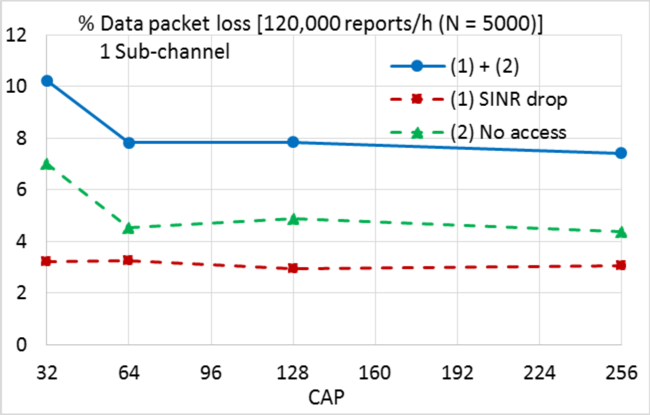


Figure 64 : Percentage of packet loss in function of CAP length, max number of channel access attempts = 2, ***ack.***

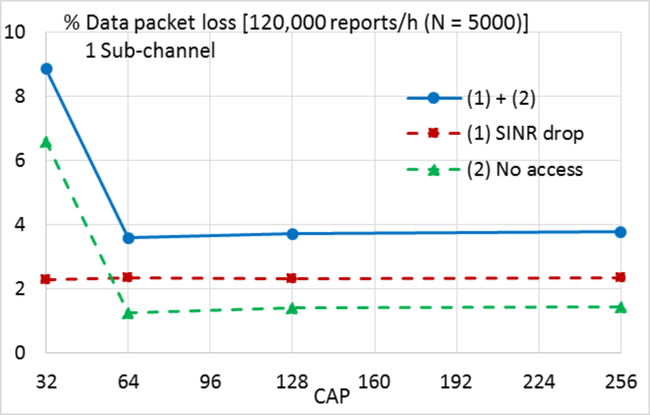


Figure 65 : Percentage of packet loss in function of CAP length, max number of channel access attempts = 3, ***ack.***

5.1.2.2 Scenario #2: UP traffic in CAP and CFP

In scenario 2, uplink traffic in the CAP and CFP is investigated. Same performance metrics are considered with a particular interest to CFP traffic since the traffic in the CAP is widely discussed in scenario 1. Therefore, by keeping the traffic in the CAP, the latency, the percentage of packet loss and packet retry in the CFP are mainly evaluated.

Figure 66.a and *Figure 66*.b show the CDF of achieved latency for periodic reports in the CFP with 1 sub-channel and with 12 sub-channels, respectively. The latency in this case includes the latency for sending the RREQ, receiving the notification in the beacon and sending the report. Similar behaviour can be observed regarding the latency with respect to the traffic density and the number of sub-channels. Indeed, this latency significantly increases in the case of 1 sub-channel due to the retransmissions of RREQs. *Figure 67* shows that 20th percentile of SINR values are improved by 10 dB with low traffic load in the case of 1 sub-channel. In the case of 12 sub-channels, there is no significant impact on latency and SINR. The degradation of SINR values for reports in the CFP (10 dB) is less than the degradation of SINR values for reports in the CAP (28 dB). This is because dedicated resources have been reserved for the devices for sending reports.

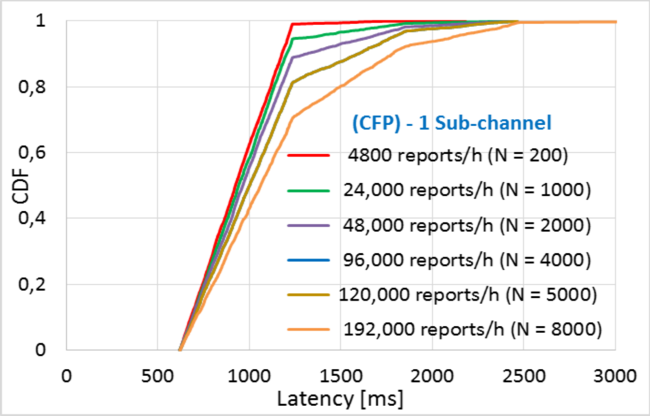


Figure 66.a: CDF of latency for periodic reports in CFP; one sub-channel is assumed available.

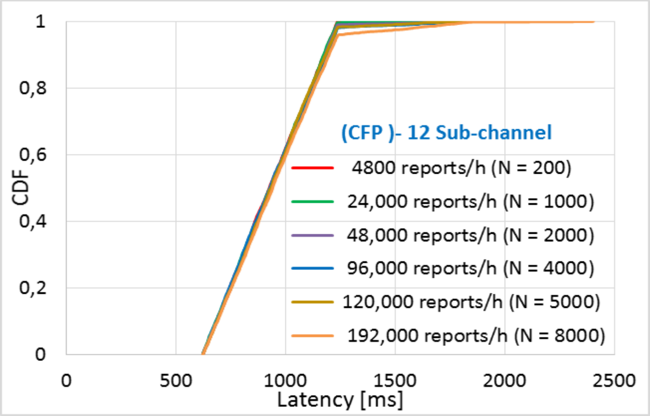


Figure 66.b: CDF of latency for periodic reports in CFP; 12 sub-channels are assumed available.

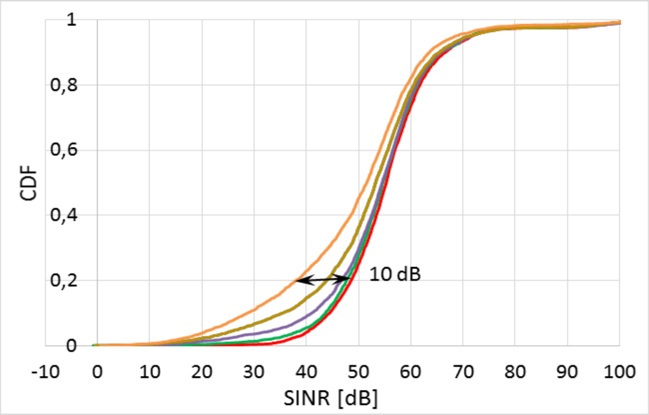


Figure 67.a: CDF of SINR for periodic reports in CFP; one sub-channel is assumed available.

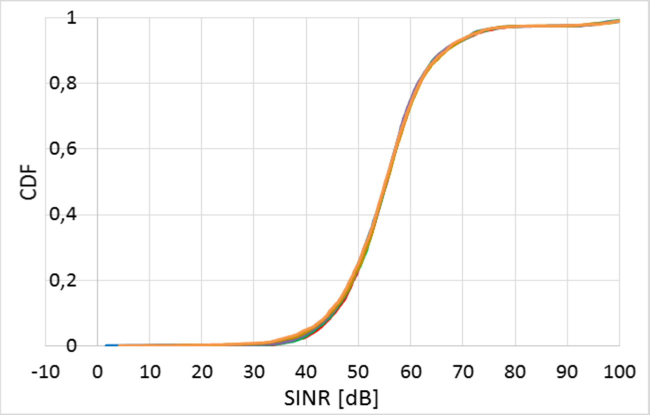


Figure 67.b: CDF of SINR for periodic reports in CFP; 12 sub-channels are assumed available.

Figure 68 shows the percentage of different causes of packet loss in the CFP. The packet in this period may be dropped either due to low SINR value (SINR data drop), either because that the RREQ has been dropped (SINR RREQ drop) or the RREQ has not sent after reaching a maximum number of channel access attempts (No access RREQ).

As can be seen, the main reason of packet loss in the CFP is the inability to send the RREQ in the CAP (No access RREQ) due to the huge amount of access in the case of one sub-channel. For example with N = 8000 devices, the percentage of packet loss is equal to 23 %, in which packet loss due to “No access RREQ” is about 20 %. The percentage of packet loss due to RREQ drop is marginal (3%) while the percentage due to low SINR value can be considered negligible (< 0.1 %) in this case. However, in the case of 12 sub-channels the percentage of packet loss in the CFP is almost negligible (< 0.15 %). *Figure 69* shows the percentage of packet retry in the CAP, in the CFP as well as the percentage of RREQ retry. As can be see, the percentage of packet retry in the CFP is negligible. Indeed, once the RREQ is correctly received and accepted by the SC, the packet is correctly sent. If the RREQ is either not received or not accepted, the RREQ is sent again. This can also explicate the increase of the percentage of RREQ retry.

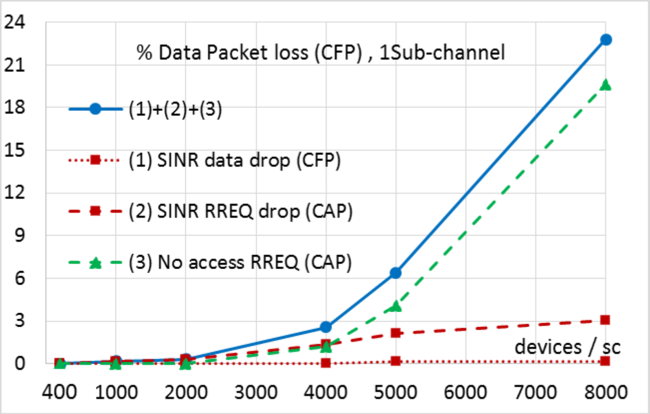


Figure 68.a: Percentage of packet loss (CFP) in function of the number of devices (1 Sub-channel).

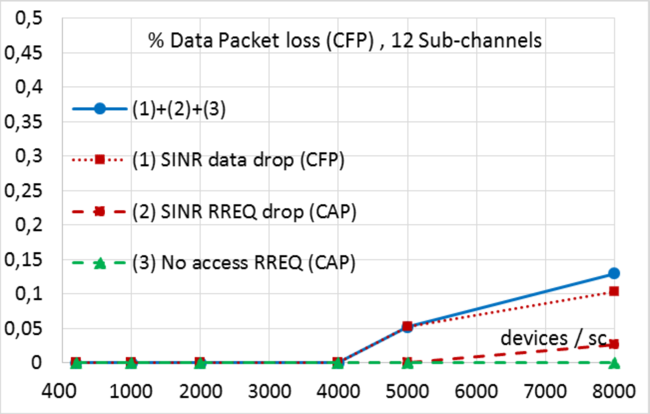


Figure 68.b: Percentage of packet loss (CFP) in function of the number of devices (12 Sub-channels).

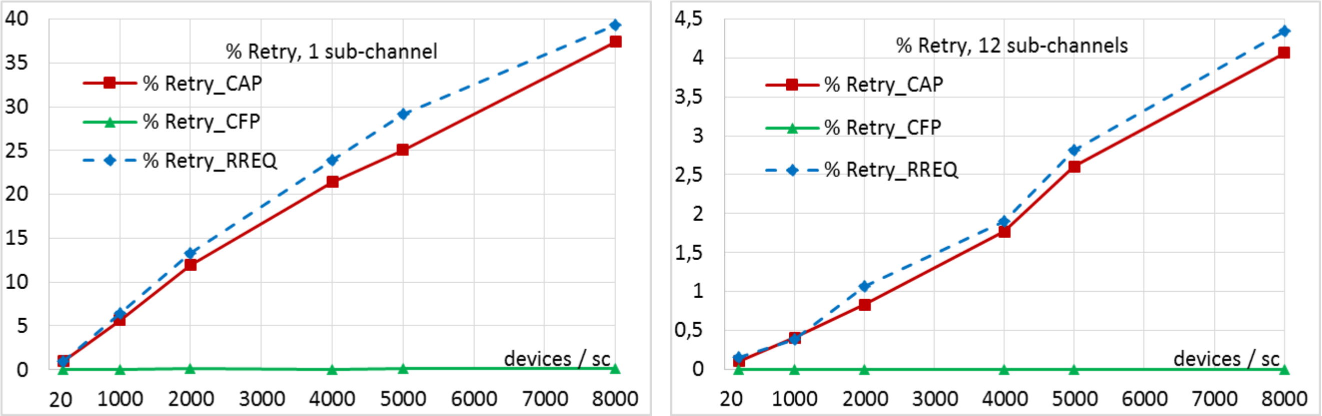


Figure 69.a: Percentage of packet retry (CAP, CFP) in function of the number of devices (1 Sub-channel).

Figure 69.b: Percentage of packet retry (CAP, CFP) in function of the number of devices (12 Sub-channels).

It is also worth to study the influence of increasing the number of sub-channels on the performance of packets in the CFP. *Figure 70*.a and *Figure 70*.b show the CDF of the latency and the SINR for periodic reports in the CFP for a traffic density of 120,000 reports/h (N= 5000). As can be seen, the latency is reduced and the SINR is improved by 5 dB with 3 sub-channels. This result is consistent with the previous result obtained in the CAP. The percentage of packet loss in the CFP is also drawn *Figure 71*.a. This percentage decreases significantly from 6 % to 0.3 % with only 3 sub-channels and become nearly negligible with higher number of sub-channels. We note also that the percentage of total packet loss (in the CFP and CAP) decreases from 13 % to less than 3.8 % and 2 % with 3 sub-channels and 6 sub-channels respectively (not presented in the figure). As previously discussed, this packet loss is mainly due to the inability to send the RREQ. Using a large number of sub-channels increases the probability of sending the RREQ and subsequently decreases the packet loss in the CFP. Moreover, the percentage of RREQ retry is decreased as illustrated in *Figure 71*.b from 30 % to 10 % approximately with 3 sub-channels.

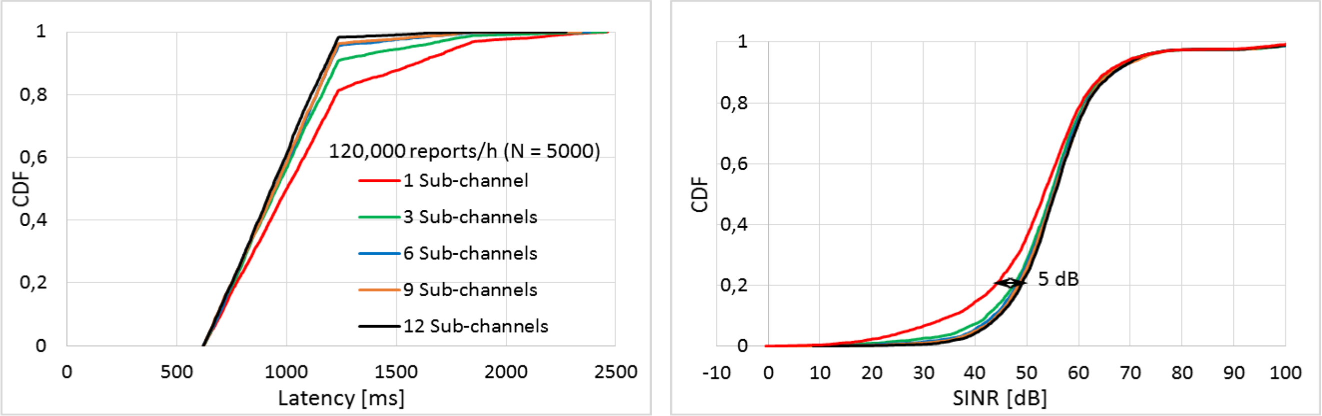


Figure 70.a: CDF of latency for periodic reports in the CFP; with variable number of available sub-channels.

Figure 70.b: CDF of SINR for periodic reports in the CFP; with variable number of available sub-channels.

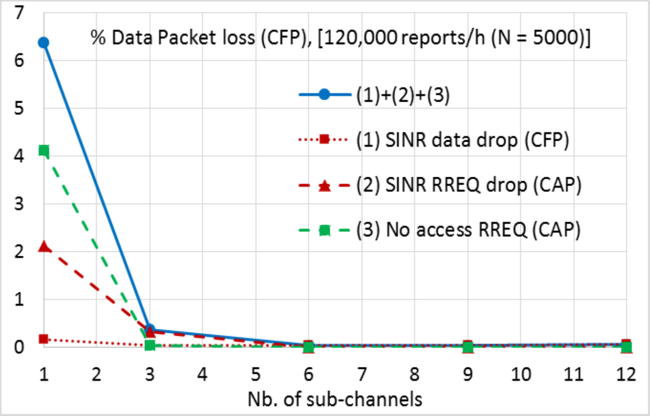


Figure 71.a: Percentage of packet loss (CFP) in function of the number of available sub-channels.

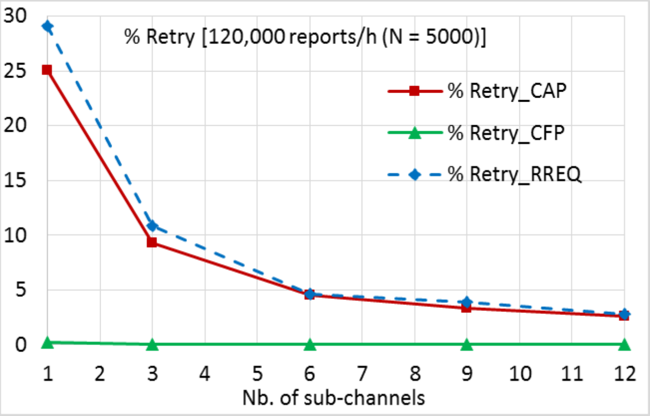


Figure 71.b: Percentage of packet retry in function of the number of available sub-channels.

5.1.2.3 Scenario #3: UP/DL traffic in CAP and CFP

In this scenario UP and DL traffics in the CAP and the CFP are considered in a more realistic traffic patterns. The focus in this scenario will be in the DL traffic related to the transmission of network commands. UP traffic is still simulated because it generate traffic load, which will impact the performance of the system.

The latency to response to NC and the energy consumption are the most critical metrics that must be investigated in DL mode. Another important aspect is to evaluate the percentage and the reason of NC failure. The failure of receiving network command can be related to the failure to receive the notification or the failure to receive NC in spite of receiving the notification. The failure to receive NC may be either due to low SINR value, the device is not able to correctly decode the packet, or to the loss of receiving the beacon.

By increasing the traffic density in the CAP and the CFP, the failure to receive network command can be considered almost negligible in all cases, e.g., the percentage of NC loss is less than 0.1 % with one available sub-channel. There is also no loss of receiving the beacon; the device is able to correctly receive and decode the beacon. Indeed, in the scenario, we suppose that there is no collision between beacons and CFP parts of others SCs. The SCs send their beacons in different periods. The interference may happen between data packets and beacon packets or between data packets. In the case where a response is required, the loss of response is due to the loss of receiving the NC itself.

For the uplink traffic in the CAP and the CFP, similar results have been found as discussed in previous scenarios in regards to the latency of sending reports, the percentage of packet loss and the percentage of packet retry. A slight increase of RREQ retry (2 %) in case of 1 sub-channel with a high traffic load is observed, this is mainly due to lack of resource when a response to the NC is scheduled in the CFP.

The latency to response to NC has been evaluated with the increase of traffic load and the number of available sub-channels. We note that traffic load will have no impact on this latency, since the SC schedules the NC and the response of the NC in the CFP. Table 21 shows the mean, the minimum and the maximum latency to receive the network command with respect to the wakeup period with 1 sub-channel and 12 Sub-channels. As can be seen, the number of available sub-channels does not have a significant impact on the latency, a maximum delay of 1 or 2 superframe durations can be observed in case of 1 sub-channel. This is because if no resource was found available to send NC, the NC is scheduled to be sent in the next superframe. We note that the frequency of sending NC as well as the number of devices able to receive NCs, are limited in the SC.

Table 21: Latency of receiving NCs

	1 Sub-channels			12 Sub-channels		
Latency / T_W	Mean	Min	Max	Mean	Min	Max
1 s	1,543529	1,238832	1,847316	1,544423	1,240452	1,850592
1 min	60,56851	60,21765	61,27382	60,52263	60,21772	60,83185
5 min	300,7644	300,4457	301,2593	300,7515	300,4453	301,0605
10 min	600,6706	600,2723	601,689	600,5804	600,2728	600,8931

For energy consumption, 4 different states are considered (sleep, idle, Rx and Tx). The energy consumption is evaluated by computing the energy consumed at each stage. The values that have been considered in this analysis are typical consumption values for low power transceivers; they are given in *Table 22*

Table 22: Current drain values in the different transceiver states

Mode	Current drain
Sleep	500 nA
Idle	1.7 mA
TX	17 mA
RX	16 mA

Two energy consumption models have been investigated as discussed in D5.1. In the first mode, the device is in sleeping mode then wakes up asynchronously at T_w, listens to the channel and synchronizes with the beacon. In the second mode, the device is always synchronized with the beacon and listens to all beacons if its wake-up period T_w is less than the wake-up threshold T_{th}. *Figure 72* illustrates the total energy consumption as well as the consumption on each state of NC devices using these two modes. As can be seen that the total consumption is mainly due to listening to the medium (Rx). In mode 2 (dotted line in the figure), a wake-up threshold of 5 min is considered, therefore the device still synchronize to the beacon if it has a wake-up period less than 5min. Comparing both modes, the energy consumption decreases significantly in mode 2. The intersection of two curves corresponds to an equal consumption; this intersection arises at $\mathrm{T_w} = 250\mathrm{s} = 4.1\ \mathrm{min}$, which validate the energy consumption modes previously discussed in Annex.

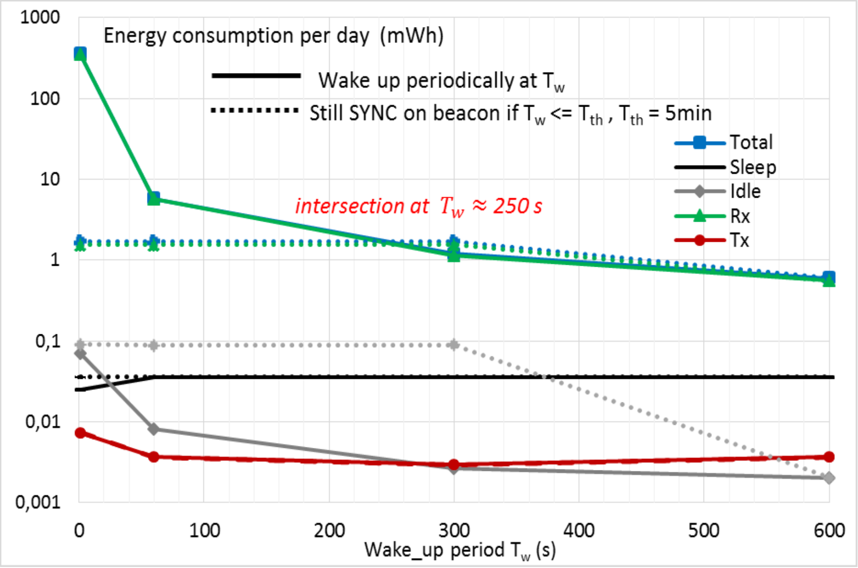


Figure 72: Energy consumption per day of NC devices

5.1.3 Benchmarking assumptions and methodology

In all previous simulations, the MAC design for IoT traffic operating in the 868 MHz band has been evaluated on system level. However it is useful to compare the performance of the proposed MAC with other systems. However, the systems may differ in their functionalities, as well as different assumptions may be considered in the simulations. Therefore, it will be difficult to give an accurate comparison of performance metrics. Through relatively adapting system parameters, it could be possible to give a rough order of magnitude comparison.

Since the traffic pattern has been derived from cellular IoT, in this section the proposed MAC design is compared with Cellular IoT (C-IoT) system based on clean state concepts. The capacity and latency metrics are considered in the comparison. The capacity metric is defined as spectral efficiency in number of reports/hour. This capacity is evaluated by running system level simulations with MAR periodic traffic model (80%) and network command traffic model (20%). The latency is evaluated for uplink reports generated by MAR periodic reporting. This latency includes the time to synchronize to the network and the time for an access attempt from the device till the time to successfully receive the UL application layer payload at the base station.

5.1.4 Benchmarking results

For capacity comparison, the same amount of generated traffic shall be considered in both systems. This can be achieved through adapting the number of devices. The considerations and assumptions used for both systems for capacity comparisons are as follows:

- For C-IoT, the *capacity per sector* metric is considered in the comparisons. The uplink traffic is generated taking into account the uplink reports and the half of the NC sessions corresponding to devices' responses. Therefore, the generated traffic corresponds to 10.08 N_{MS} reports per sector per day, where N_{MS} is the number of MSs configured per sector (see [14] for more details]. The total number of reports generated per sector during simulation time corresponds to $\mathrm{N_{reports/\,sim}} = 10.08 \times \mathrm{N_{MS}} \times \mathrm{T_{sim}}/86400$.
- The capacity of the system is determined by increasing the number of offered loads denoted by "Number of devices or number of MSs per sector". The capacity is given as: $\mathrm{C_{reports/h}} = (\mathrm{N_{reports/sim}}/\mathrm{N_{cell}}) \times (3600/\mathrm{T_{sim}})$, where $\mathrm{N_{reports}}$ denotes the total number of successful uplink reports from all cells, N_{cell} is the number of simulated cells.

- For the proposed MAC design for IoT in Speed-5G, the *capacity per SC* metric is also considered. Since, a reporting interval of 15 min is considered in the simulations, the generated uplink traffic is equal to $86.4\ N$ reports per SC per day, where N is the number of devices by SC. To be able to compare the capacity of this MAC design with C-IoT proposals as fairly as possible, we have considered the same amount of generated uplink traffic per sector in C-IOT solutions and per SC for this proposal. To do that, given that the traffic generation rate is smaller in C-IoT solutions, we have decided to consider C-IoT results obtained by increasing the number of C-IoT devices so to have the same number of reports per day for both options.

Capacity comparison results are presented in Figure 73. The back line corresponds to the ideal capacity where all uplink reports are assumed to be successfully delivered by the system.

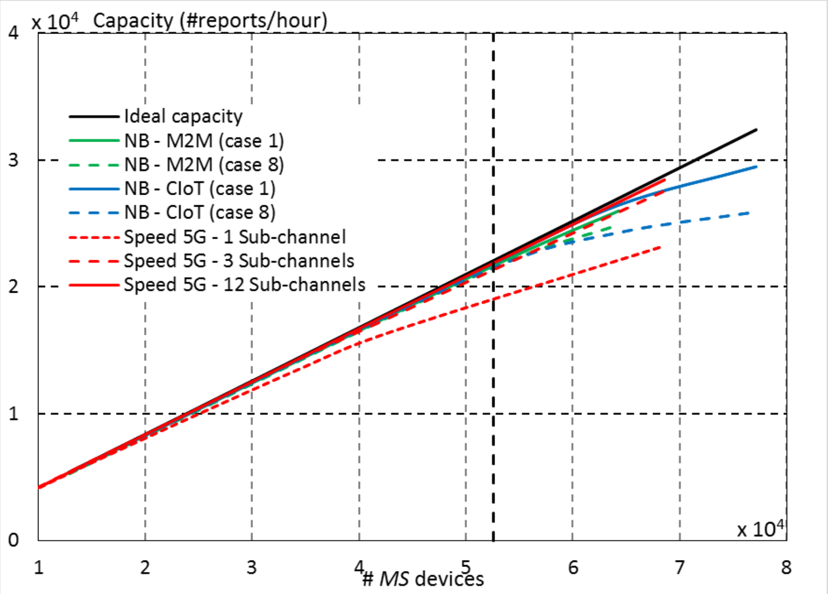


Figure 73: Capacity comparison in (# numbers of reports/hour)

In C-IoT, eight simulation cases have been considered that correspond to the several scenarios with and without IP compression, and with different parameters related to inter-site correlation coefficient. Scenarios case 1 and case 8 are only presented in the Figure corresponding to best and worst-case scenarios. The target number of devices within the sector is assumed 52547. For this number, there is no significant difference between the actual number of reports and the ideal number of reports. This implies that the capacity of the system is sufficient to support the target number of MSs per sector. In the proposed design, as can be seen with one sub-channel, the capacity of the system is far from the ideal capacity. However, with the increases of the number of available sub-channels, the achieved capacity is closer to the ideal capacity, and this target number of devices is also supported. As can be also notify, that beyond this target number, the proposed MAC design is able to achieve a capacity more closely to the ideal capacity.

For latency comparison, the latency for uplink reports generated by MAR periodic reporting is considered. The 50th percentile latency with offered load of 52547 MSs per sector with C-IoT and an equivalent number of 86571 devices per SC are summarized in Table 23. As can be seen, in both systems, the target latency less than 10s for mIoT applications is achieved. However, with the proposed MAC design the latency achieved of sending periodic reports is lower than other systems. This is mainly due to the low overhead length, and on the synchronization and random access procedure. However, it is worth mentioning that C-IoT results corresponds to complete systems whereas in our case, we have a more idealistic protocol where overhead is needed to make it useable in the context of C-IoT, which may induce extra-latency.

Table 23: The 50th-% latency for MAR periodic UL reports

NB - M2M (case 1)	1.21 s (N = 52547 devices/ sector)
NB - M2M (case 8)	2.17 s (N = 52547 devices/ sector)
NB - CIoT (case 1)	1.51 s (N = 52547 devices/ sector)
NB - CIoT (case 8)	2.63 s (N = 52547 devices/ sector)
Speed 5G - 1 Sub-channel	= 0.5 s (N = 86571 devices /SC)
Speed 5G - 12 Sub-channels	< 0.5 s (≈ 0.4 s) (N = 86571 devices /SC)

5.1.5 Evaluation Summary

In this set of results, the performance of MAC design for IoT traffic operating in 868 MHz band has been investigated using system-level simulations with different traffic patterns. Performance evaluation in terms of several important metrics (latency, % packet loss, % packet retry) has been presented. It is shown that increasing the traffic density inevitably increases the percentage of packet loss and the percentage of packet retries due to the increase of interference levels in the network especially with one sub-channel. This packet loss is mainly due to the failed channel access attempts.

Upon increasing the number of available sub-channels, the majority of devices experience a successful access attempt and the packet loss is then principally due to drop in SINR. The percentage of packet loss with 1 sub-channel was found to be around 30 % with a traffic density of 192,000 reports/h (N = 8000). This percentage has been significantly decreased by increasing the number of available sub-channels and it was found to be less than 4 % in the case of no acknowledgment and almost negligible (<0.1%) in the case of acknowledgment with 12 sub-channels.

The impact of the CAP length was found to be less significant compared to the impact of the number of sub-channels. As for DL traffic, the results indicate that network commands have been successfully delivered by the SC to the devices, within the specified latency, with a failure rate of less than 0.1 %.

In addition, we have shown that it will be more energy efficient for the device to listen and still synchronize to all beacons if it has a wake-up period less than the wake-up threshold, which has been found to be 5 min.

5.2 MAC Design #2: Broadband wireless access in dense hetnets

This section shows the preliminary results of this MAC design for the extended suburban scenario and the virtual office. The extended suburban results are focused on LTE as the baseline results and The virtual office results are focussed on channel coexistence setting the benchmark with WIFI and LAA. The performance of this MAC design should be assessed in the coming deliverable D5.2.

5.2.1 Benchmarking assumptions and methodology

Extended suburban *(LTE HetNet for xMBB)*

The Extended Suburban HetNet scenario has been defined in Speed-5G for the purpose of improving capacity in highly typical European suburban areas, which is also similar to the suburbs of some major US cities as well as in some regions in Asia. This scenario is very meaningful in order to evaluate the 5G HetNet performance in both space and time in such a typical suburban environment.

The Extended Suburban HetNet scenario is comprised of a mixture of residential areas, green spaces and a single large commercial area. In the following, the typical elements that form part of the Extended Suburban HetNet scenario are listed and briefly described.

- Residential areas, represented by blocks of houses equally spaced in the *x* and *y* direction.
- A big commercial area, i.e., the typical area used up by a shopping mall.
- Recreational areas, including parks and green spaces.
- Streets, which act as the dividers between the above areas.

The characteristics of this scenario provides a high flexibility due to it contains several areas of interest that can be investigated individually, making it particularly suitable to perform different studies using the same base scenario. The entire scenario is shown in Figure 74, which occupies an area of roughly 700 m by600 m. The red rectangle highlights the area used to perform the initial simulations, whose results are provided in the following sections.

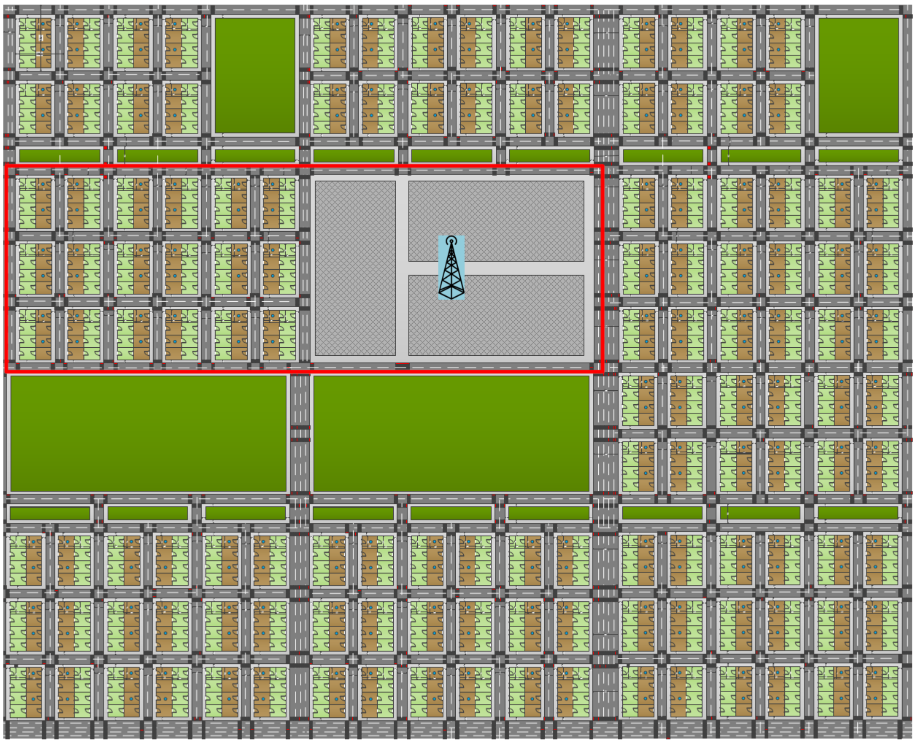


Figure 74: Extended Suburban HetNet Scenario

The residential areas modelled by the Extended Suburban HetNet scenario are comprised of blocks of houses, separated by streets parallel to the houses. Each block is composed of four houses and each house is equipped with a backyard, according to the typical building structure of houses in suburban areas. This scenario also models the pavements installed between the streets and the houses themselves.

In this baseline scenario, one small cell home eNodeB (HeNB) is installed every two houses, and a single three-sector macro eNodeB (eNB) base station is installed in the centre of the big shopping area, on top of the roof at the height specified in next section. The orientation of each of the three sectors is also specified in the following section.

The main simulation parameters for the Extended Suburban HetNet scenario are summarized in the following Table 24.

Table 24: LTE Simulation Parameters

LTE Simulation Parameter	Small cell layer: Indoor scenario	Macro cell layer: Outdoor scenario
Distance-dependent path loss	3D distance between BS and UE is applied	
Propagation model	ITU P.1238 Propagation	ITU P.1411 Propagation
Wall penetration loss	7 dB for residential buildings (concrete walls with windows) 15 dB for commercial buildings (concrete walls without windows)	
Standard deviation of the normal distribution used to calculate shadowing	Indoor nodes: 8 dB Internal walls: 5 dB	Outdoor nodes: 8 dB External walls: 5 dB
Mobility model of UEs	Stationary	
Total BS transmit power	21 dBm for 20 MHz	46 dBm for 20 MHz
UE power class	21 dBm	
Bandwidth	20 + 20 MHz (FDD)	
Antenna pattern	2D Omni-directional	Three-sector directional antenna with antenna orientations = {0, 120, -120} degrees
Antenna Height:	3.5 m	35 m
UE antenna Height	1.5 m	
BS Noise Figure	5 dB	5 dB
UE Noise Figure	7 dB	
Antenna gain of BS including connector loss	0 dBi	17 dBi
Antenna gain of UE	0 dBi	
Number of UEs	5 UEs per small cell. Ratio of Small cell/Macro cell UEs: 80/20. The users attached to the Small cell layer are mostly indoors, while for the macro layer they are composed of a mixture of outdoor and indoor UEs, randomly spread over the whole simulation area.	
UE dropping for each network	Randomly dropped	
Minimum distance (Inter-site 2D distance)	18 m	700 m

LTE Simulation Parameter	Small cell layer: Indoor scenario	Macro cell layer: Outdoor scenario
Data traffic model	Full buffer UDP	
Thermal noise level	–174 dBm/Hz	
Number of antennas	2x2	
UE receiver	MMSE	
Frequency Band	2.6 GHz	800 MHz
Scheduler	Proportional Fair both in Frequency and Time domains	

Virtual Office *(LTE-LAA for xMBB)*

While the results for the Extended Suburban scenario LTE-based, **the virtual office initial simulations results are focused on multi-RAT coexistence.** The simulations are done over the same layout as proposed in [23] by the 3GPP. Using this kind of standard layout, the obtained results can easily be compared with other studies.

This scenario considers two operators deploying four SCs each in the single-floor building. The SCs of each operator are equally spaced and centred along a building (120m by 50m). The distance between the UEs and SCs is random. Figure 75 shows the scenario layout. The preliminary results are focus on the LAA and WiFi coexistence.

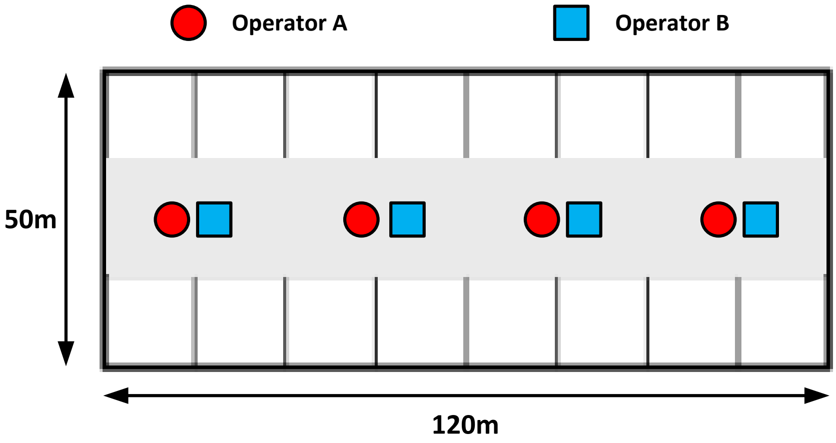


Figure 75: Virtual office layout

Table 25 summarizes the main parameters used to perform the virtual office simulations. It is important to note that this simulation does not include the macro layer so all the UEs are connected to the indoor small cells.

Table 25: Main simulation parameters for unlicensed band use on virtual office scenario

System bandwidth per carrier	20MHz
Frequency Band	5.18GHz
Number of carriers	1 for DL
SC TX power	18 dBm
UE TX power	18 dBm
Distance-dependent path loss	IEEE 80211ax Indoor Small BSS Hotspot[24][25]
Antenna pattern	2D Omni-directional is baseline; directional antenna is not precluded

Antenna Height:	6m
UE antenna Height	1.5m
Antenna gain + connector loss	5dBi
Antenna gain of UE	0 dBi
Fast fading channel between eNB and UE	ITU InH
Number of UEs	5 UEs per cell per operator
UE dropping per network	Randomly dropped
Minimum distance Cell - UE	3m
Traffic model	Constant Bit Rate UDP 400 kbps
SC noise figure	5dB
UE noise figure	9dB
UE speed	0km/h
Cell selection criteria	For LAA UEs, cell selection is based on RSRP in the unlicensed band. For WiFi STAs, cell selection is based on RSS (Received signal power strength) of WiFi APs. RSS threshold is -82 dBm.
UE Bandwidth	20 MHz for LAA and WiFi

5.2.2 Benchmarking results

Extended Suburban - The simulation area whose results are provided in this section refers to the area highlighted by the red rectangle drawn in Figure 74. Besides the simulation parameters listed in Table 24, some additional ones that are relevant to this particular simulation are provided in

Table 26. The preliminary simulations are done using the standard LTE RAT only. The results are obtained without using any of the studied eDSA techniques. The main idea is to have these results as the base to compare the network improvement when our proposals are applied.

Table 26: Additional simulation parameters for the subset of the extended suburban scenario

additional LTE simulations parameters	small cell layer	macro cell layer
Downlink EARFCN	3100	6300
Number of cells	36	3 (equivalent to a single three-sector macro eNB base station)
Number of users	180 (indoor users randomly deployed within the whole set of houses representing the residential areas)	45 (mixture of indoor and outdoor users randomly dropped over the whole simulation area)
Closed Subscriber Group	Closed (same group for all cells)	Open
Duration of simulation	10 s	
Number of independent seeds	24	

Figure 76 and Figure 77 show the pathloss into the selected area for the small cell and the macro layer respectively. These images capture only a snapshot of the radio propagation; which represents only one precise time instant of the shadowing process that the radio signals undergo. Additionally, the strange salt-and-pepper effect is also related to the particular sampling frequency that was used to generate these images, which in turn affects the relatively low resolution of these images.

small cell layer

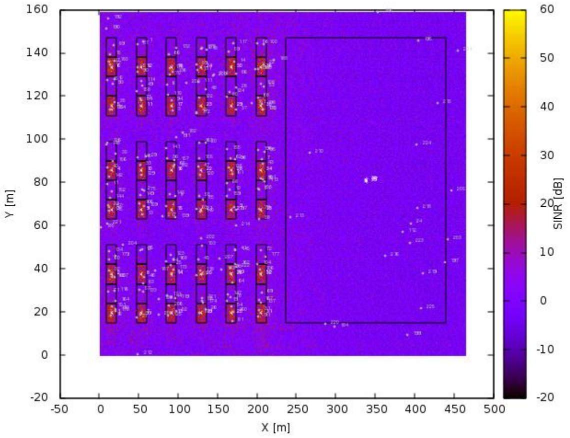


Figure 76: HeNBs installed indoors and every two houses at 2.6GHz.

macro cell layer

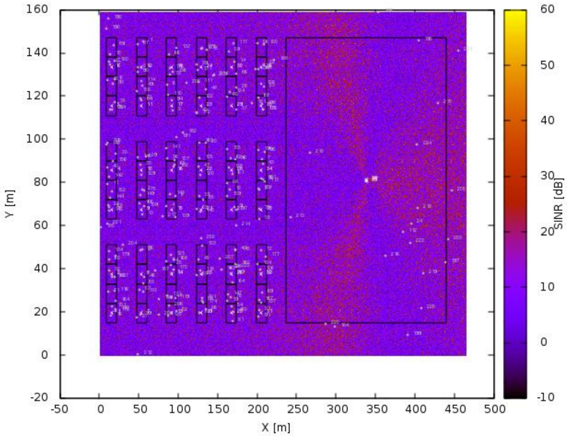


Figure 77: Three outdoor eNBs cells at 800MHz

In Figure 78 and Figure 79, the simulation results for the subset of the Extended Suburban scenario under consideration are provided. In order to obtain these results, 24 independent simulations have been performed and combined. The focus of these initial results is on throughput and latency, for both the small cell layer and the macro cell layer.

Delay

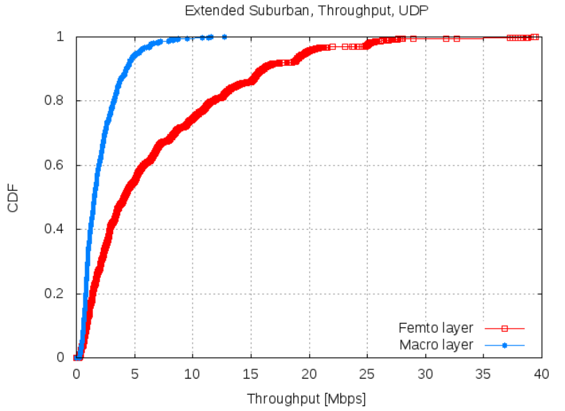


Figure 78: Cumulative Distribution Function (CDF) of the achieved throughput per user

Throughput

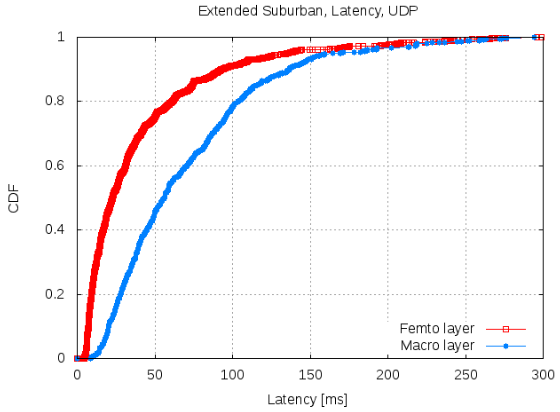


Figure 79: CDF of the served latency per user

The dropping of the users in the scenario is random and the area depends on the desired cell to be attached, therefore for each independent drop the different users will be placed at different locations and will therefore experience different SINR levels. Since the simulation focus is set on the SC and the macro layers' delay and throughput evaluation and, not in HetNet SON functions which try to mitigate interferences, each layer has a different frequency. The macro cells operate in the 800MHz frequency band while the SCs cells are in 2.6GHz frequency band, avoiding interference over these two heterogeneous layers. On the other hand, nodes belonging to the same layer are transmitting in the same frequency band and consequently, it will indeed interfere with each other.

Virtual Office - The preliminary results are obtained configuring two different RATs, one RAT per operator. The operator A is configured to use LAA while the operator B uses WiFi. The parameter modified on the simulations is the Energy Detection (ED) threshold used in LBT. This parameter is modified from -52dBm to -82dBm in steps of 10dB. Other parameters remain equal for each simulation. The following parameters, in Table 27, are related to how the simulation is done, instead of to the simulated scenario itself.

Table 27: Additional simulation parameters for the virtual office under consideration

additional LTE simulations parameters	small cell layer
Downlink EARFCN	255444
Number of cells	4 per operator
Number of users	20 per operator
Duration of simulation	20 s
LBT Energy Detection Thresholds	-52, -62, -82
Number of independent seeds	72

The cumulative distribution function (CDF) throughput and the CDF latency per user results are shown in Figure 80 and Figure 81respectively and demonstrate how the ED variation affects.

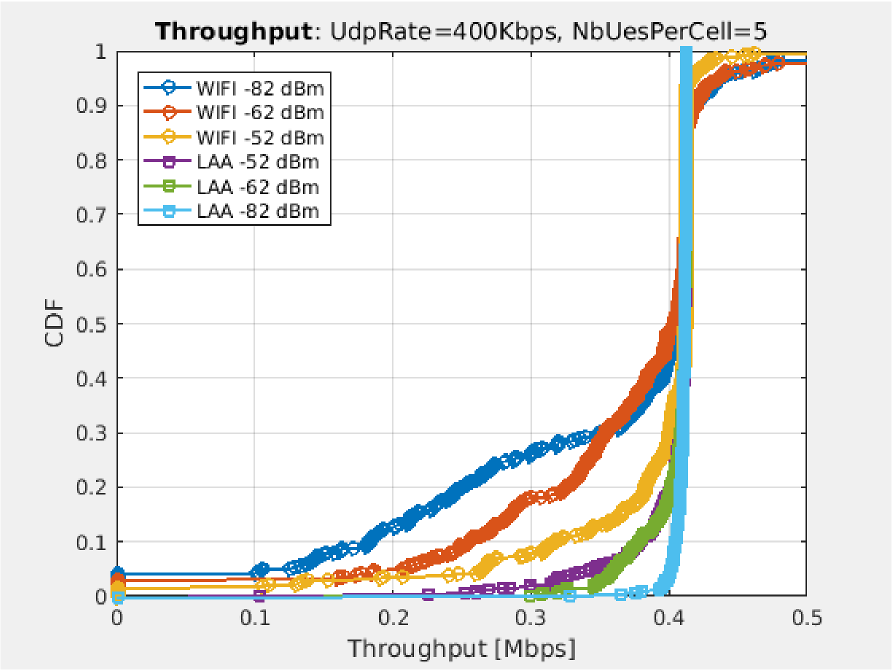


Figure 80: CDF of the served throughput per user

Lower ED thresholds imply that LAA will transmit more frequently since the restrictions for doing it are relaxed. The consequence is, that as the ED threshold is lower (as much of time the channel is occupied by LAA), and thus WiFi has less opportunities to find a free channel in which to transmit. Figure 80 shows the LAA and WiFi CDF throughput for different ED Thresholds. Itis possible to check the expected behavior and how, a -82dBm threshold makes that all throughput of the LAA users is transmitted while the 30% of the WiFi users are not reaching even 300kbps. On the other hand, when the network is configured to use a high threshold, -52dBm, the network coexistence is achieved due to the fact that the LAA and WiFi users' throughputs are almost the same.

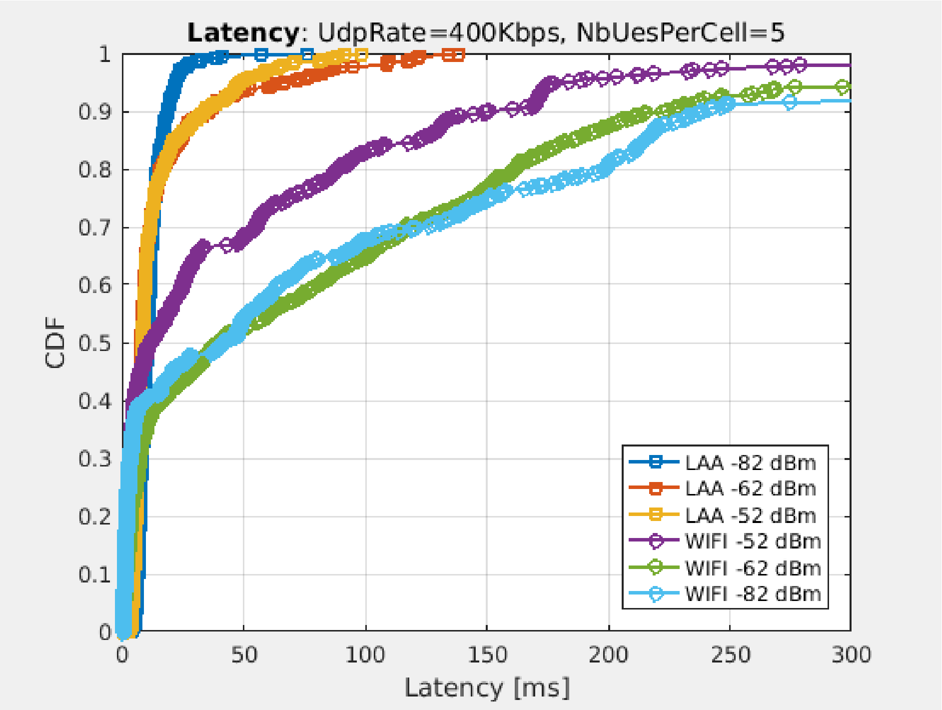


Figure 81: CDF of the achieved latency per user

In Figure 81 is possible to obtain two different conclusions. The first one is that, when the system has more capacity to serve the offered traffic, the latency decreases. LAA and WiFi have lower latencies with lower and higher ED thresholds respectively since more throughput is achieved. The second conclusion is that LAA and WiFi have different latencies. When the ED threshold is set to -52dBm, the coexistence in the network is achieved but, even that, a 10% of WiFi users may undergo latencies higher than 150ms while the maximum LAA latencies does not reach 100ms.

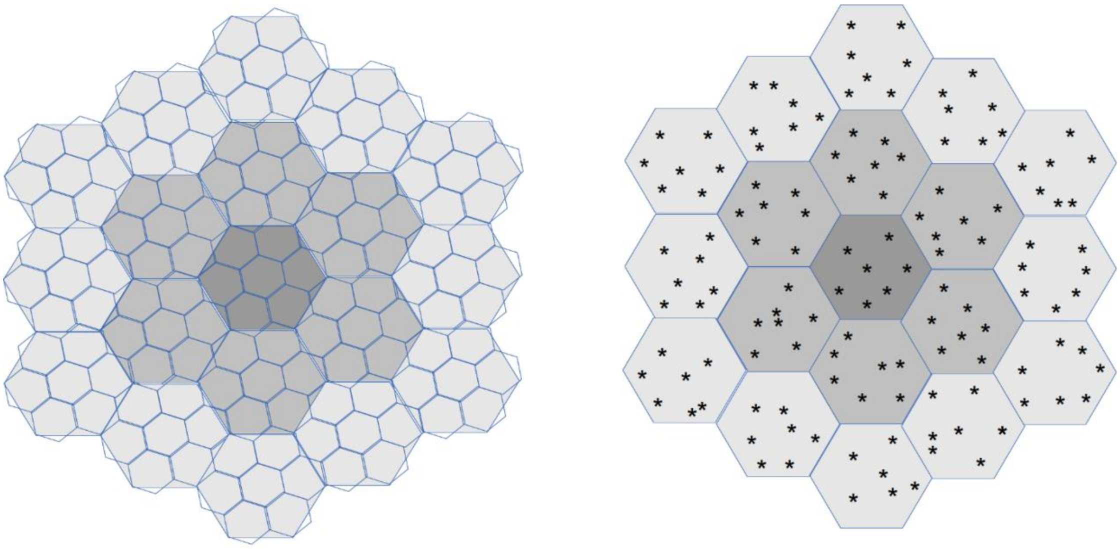
5.2.2.1 Evaluation Summary

The results provided in this section focus only on LTE. As an extension of these results, the designed MAC needs to be integrated into the system level simulator with RRM algorithms and the novel MAC framework. Specifically, in future deliverable(s), the performance for the same layout, but having one SC installed per household, instead every two, should be investigated in the extended suburban scenario.

5.3 MAC Design #3: Decentralized dynamic DCS-MAC for ultra-dense networks

This section presents preliminary performance results of the DSC-MAC design. As this design focuses on the broadband wireless use case, the scenario considered for evaluation in this section assumes full SC coverage. In order to achieve full SC coverage, high SC density per km^2 is required, corresponding to small inter-site distances. In this particular study we focus on the inter-site distance of 50m – performance evaluations under different inter-site distances will be provided in deliverable D5.2.

Different deployment strategies can be considered for the SCs supporting the DCS-MAC which include **regular (i.e., hex-grid like) and irregular (i.e., random) deployment**s. Regular deployment of clusters of SCs can be also investigated (such deployments assume that location of clusters of SCs in the simulation scenario is regular whilst the deployment of SCs within the cluster can be either regular or irregular). In this study we focus on investigation of regular single cell cluster outdoor deployment. Results for other types of deployments (including indoor deployments) will be provided in D5.2 deliverable.



Regular/planned small cell layout within a cluster area

Irregular/unplanned small cell layout within a cluster area

Figure 82: Regular/Planned cluster layout

The proposed MAC has been simulated using ns-3 simulation platform. In order to minimize border effects wrap-around with properly selected number of rings has been considered. Determining the proper number of rings for wrap-around has proved necessary to allow accurate simulations of system which rely on different forms of channel measurements for channel access (see e.g. [52]).

Besides providing initial evaluation of the DCS-MAC, this section also provides initial benchmarking results comparing the proposed MAC with the IEEE 802.11 standard MAC. More comprehensive comparison as well as evaluation against LTE MAC will be provided in the D5.2 deliverable.

5.3.1 Scenario-specific simulation assumptions and parameters

This section provides simulation assumptions and parameters for the initial evaluation of the DCS-MAC. The parameters of the considered deployment scenario are summarized in Table 28 whilst different DSC-MAC settings are presented in Table 29.

Table 28: Scenario parameter settings for initial DSC-MAC evaluation

Parameter	Value
Network layout	Regular (Hexagonal) grid
Wrap-around	Yes (6 rings)
STA/AP height	1.5m / 10 m
STA distribution	Random/uniform distribution
Path loss model	Log-distance model with path-loss exponent of 3.5
Shadow fading model	Not considered
Fast fading model	Not considered
Mobility	Not considered
Traffic model	Full buffer (saturated model)

Traffic type	Non-elastic (UDP)
Traffic asymmetry	20% uplink, 80% downlink traffic
Packet size (size of the packet transmitted on the air interface, i.e., with MAC, IP and TCP overheads)	1500 bytes (Application layer packet size: 1424 bytes)
Frequency band	2.4GHz (ISM band)
AP density	462/km^2 (ISD=50m)
UE density	Variable
Ptx	-55 dBm/Hz

Table 29: DSC-MAC parameter settings for initial evaluation

Parameter	Value
Number of slots per frame	24 (non-adaptable)
Number of frequency channels available for access	10
Bandwidth of individual frequency channels (including guard bands)	2MHz (non-adaptable)
Number of transceivers on BS side	Ranging from 1 to 10
Number of transceivers on UE side	1
Rate adaptation	Considered
C-Field and preamble overhead	20% (static)

5.3.2 Simulation results and analysis

The initial performance evaluation results of the DSC-MAC design is provided in this section. More specifically, the impact of user density and the impact of aggregation on system performance is investigated. The obtained results are based on the simulation parameters defined in the previous section.

Three cases of channel aggregation are shown in the Figures below: 1) '10% BW per cell'– only 10% BW of overall BW is used for communication (i.e., 1 TRX which allows access to only 1 channel among 10 channels at a time is used on the BS side), 2) '50% BW per cell'– 5 channels are exploited for aggregation (i.e., 5 TRXs which allow access to 5 channel among 10 channels at a time are available on the BS side), and 3) '100% BW per cell'– all supported channels can be aggregated. (i.e. 10 TRXs are used by each cell).

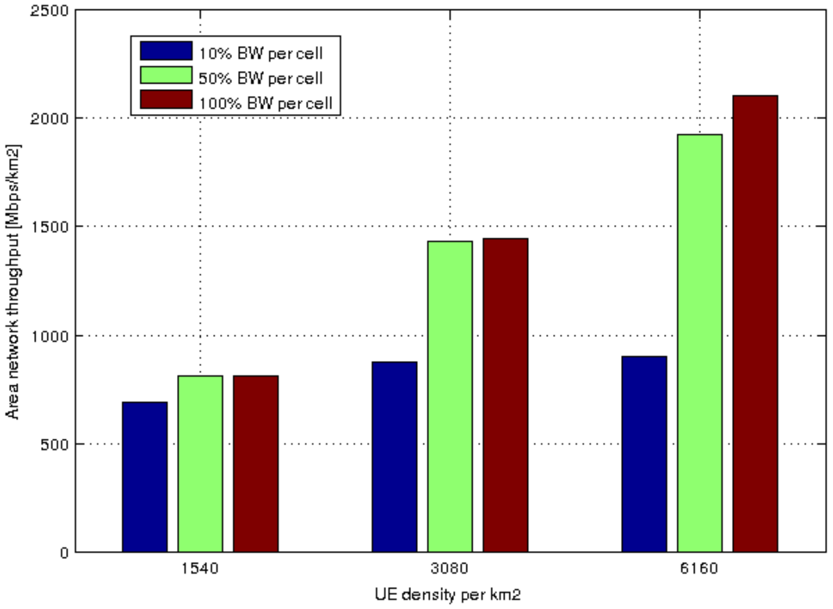


Figure 83: The impact of varying aggregation BW and UE density on the area network throughput

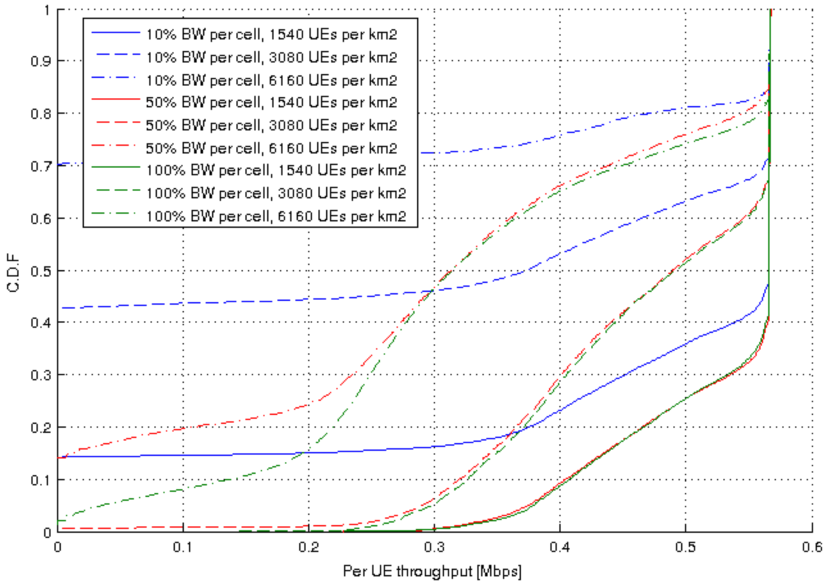


Figure 84: The impact of varying aggregation BW and UE density on the per UE throughput

The above figures present the impact of UE density (which can be directly map to network load) and aggregation level (which can be mapped to the number of transceivers with respect to the number of available frequency bands) on the area network throughput and per UE throughput. As can be seen in Figure 83, area network throughput in general increases with the UE density. The rate of the increase is however dependent on the aggregation level. For instance, the increase for the 10% BW per cell is only marginal compared to other cases and stems mainly from the fact that for higher UE density the probability of finding UEs close to BS is higher (thus resulting in better channel condition between BS and their associated UEs). This is confirmed by Figure 84, where it can be observed that for the 10% BW per cell case the number of UEs which are not handled increases to 70% for the UE density of 6160 UEs per km2. It needs to be underlined here that the user outage depicted in Figure 84 is caused by a hard limit on the number of users served which can be served by a single cell with one TRX (this problem can be limited when number of slots can be dynamically adapted), rather than interference. This can be seen in the 100% BW per cell case, where a single cell can serve all users by appropriately selecting channels through dynamic channel selection.

Further Scenario-specific results based on common simulation assumption will be provided in D5.2 deliverable.

5.3.3 Benchmarking assumptions and methodology

This section discusses methodology and assumptions for comparing the proposed MAC design with WiFi standard MAC. The parameters of the deployment scenario considered for benchmarking are summarized in Table 30 which are in line with the 3GPP[23]. The parameters settings for DSC-MAC and WiFi are presented in Table 31 and Table 32, respectively.

It needs to be highlighted here that in order to allow for a fair comparison rate adaptation has been switched off in WiFi and the DSC-MAC. Moreover, equal amount of uplink and downlink traffic was generated (i.e. 50% of Uplink and 50% of Downlink traffic). In order to allow direct comparison the results are presented in terms of area spectral efficiency.

Table 30: Scenario parameter settings for benchmarking

Parameter	Value
Network layout	Regular (Hexagonal) grid
Wrap-around	Yes (variable number of rings)
STA/AP height	1.5m / 10 m
STA distribution	Random/uniform distribution
Path loss model	ITU-R UMi based model
Shadow fading model	sigma = 3dB (LOS) / 4dB (NLOS), decorr = 10m (LOS) / 13m (NLOS), correlation between arbitrary pairs of links
Fast fading model	Not considered
Mobility	Not considered
Traffic model	Full buffer (saturated model)
Traffic type	Non-elastic (UDP)
Traffic asymmetry	50% uplink, 50% downlink traffic
Packet size (size of the packet transmitted on the air interface, i.e., with MAC, IP and TCP overheads)	1500 bytes (Application layer packet size: 1424 bytes)
Frequency band	2.4GHz (ISM band)
AP density	462/km^2 (ISD=50m)
UE density	Variable
Ptx	-55 dBm/Hz

Table 31: DSC-MAC parameter settings for benchmarking

Parameter	Value
Number of slots per frame	24 (non-adaptable)
Number of frequency channels available for access	10
Bandwidth of individual frequency channels (including guard bands)	2MHz (non-adaptable)
Number of transceivers on BS side	Ranging from 1 to 10
Number of transceivers on UE side	1
Rate adaptation	Switched off (MCS0 - BPSK modulation)
C-Field and preamble overhead	20% (static)

Table 32: WiFi parameter settings for benchmarking

Parameter	Value
IEEE 802.11 standard	IEEE 802.11g
STA/AP CCA Mode1 threshold	-62dBm
STA/AP RX sensitivity	-82dBm
Channel bandwidth	20MHz
Number of orthogonal channels	1
Beacon period	100ms
RTS/CTS	Switched off
Rate adaptation	Switched off (MCS0 - BPSK modulation)
Fragmentation	Switched off

5.3.4 Benchmarking results

This section presents and discusses initial results of proposed MAC performance compared to the IEEE 802.11 standard MAC. As mentioned earlier, more comprehensive evaluation results as well as evaluation against LTE MAC will be provided in deliverable D5.2.

Firstly, Figure 85 shows the comparison of network capacity supported by Wi-Fi and the proposed DCS-MAC. As mentioned in the previous section, the channel of 20 MHz is assumed to be available for WiFi while 10 channels of 2 MHz are assumed available for the proposed MAC. Three cases of channel aggregation are shown: 1) ‘10% BW per cell’– only 10% BW of overall BW (i.e., 1 channel among 10 channels) is used for communication, 2) ‘20% BW per cell’– 2 channels are exploited by aggregation, and 3) ‘40% BW per cell’– 4 channels with aggregation. By exploiting inherent interference diversity, the new proposed MAC adopting the dynamic channel selection can increase the network capacity compared to legacy Wi-Fi. As can be seen the proposed DCS-MAC outperforms WiFi in the considered scenario.

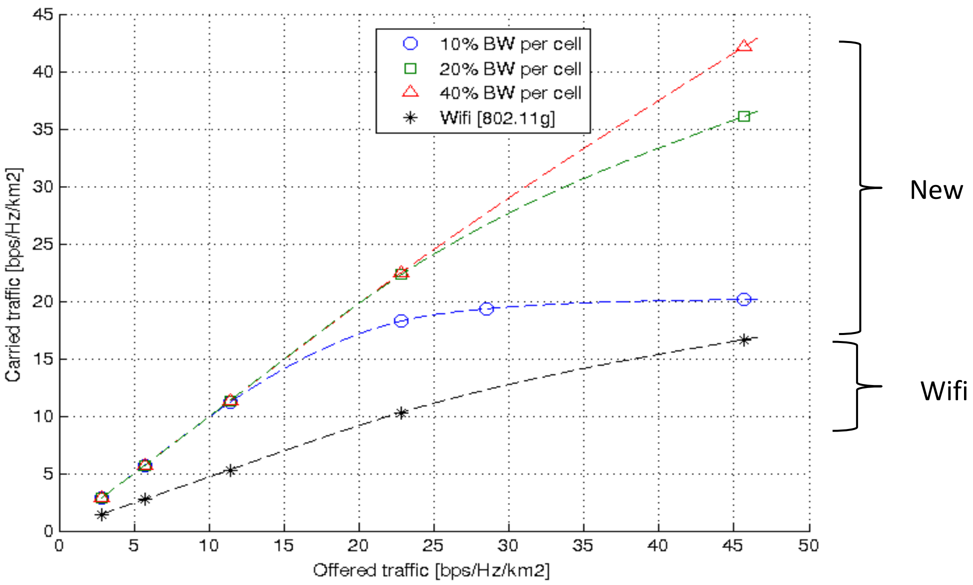


Figure 85: Comparison of network capacity performance of the proposed MAC and Wi-Fi

In Figure 86, the impact of network load on the SINR is presented for different network loads. As can be seen the dynamic channel selection mechanism prevents the use of channels below the SINR target which is set to provide the minimum required QoS. This is achieved by allowing users and base stations to dynamically change physical channels if the quality is insufficient. As can be seen, with the increase in the network load, the SINR curve becomes stepper. In the ideal case, for sufficiently large network load, the SINR curve should overlap with the red vertical dashed line indicating the SINR target. In such a situation all stations would operate at the min. required SINR.

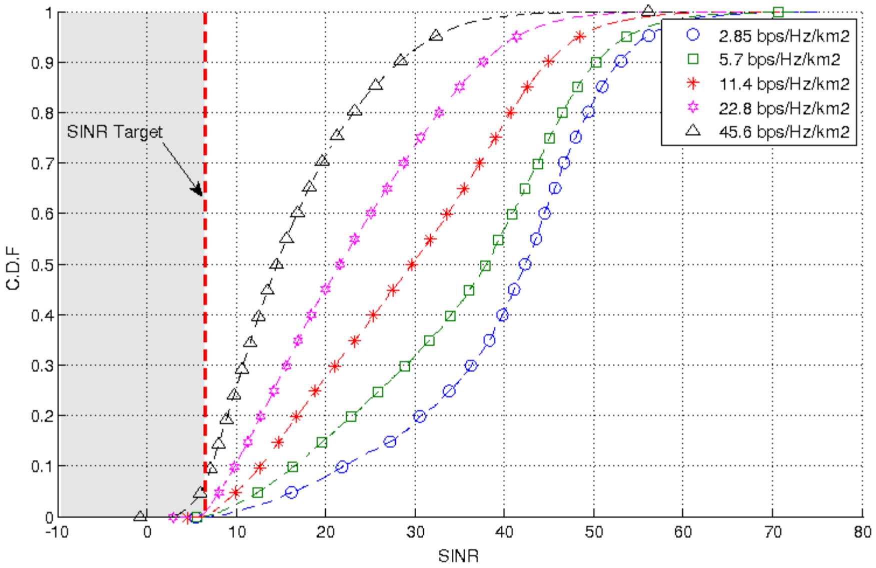


Figure 86: Performance of dynamic channel selection in the proposed MAC

5.3.4.1 Evaluation Summary

The preliminary results presented in this section show that the proposed DCS-MAC adopting dynamic channel selection helps users to use better channel with higher SNRs, thus achieving an increased network capacity. In addition, when it uses more bandwidth by aggregation, it has higher flexibility in resource allocation, leading to better performance.

In this preliminary set of results, the performance of DCS-MAC design operating in 2.4 GHz ISM band has been investigated on system level for full-buffer traffic model. The investigation focused on evaluation of the impact of UE density and aggregation level (i.e. number of TRXs on the BS side) on area network throughput and per UE throughput. Additionally, this section presented initial comparison results between the proposed MAC and the WiFi standard MAC which showed that DCS-MAC outperforms WiFi. Although the initial results are promising, it needs to be highlighted here that further investigations are necessary to confirm superiority of the proposed MAC over the WiFi.

5.4 Simulation plans for MAC assessment

As previously stated, the object of this deliverable is to present i) a high-level framework for the SPEED-5G MAC layer that is able to implement eDSA by means of multi-RAT capabilities and inter-RAT cooperation functions, ii) different MAC flavours which in a whole cover the evolutionary and the revolutionary pathway to 5G, respectively by addressing improvement of existing systems like LTE, Wifi, etc and by considering clean slate approaches to natively support multi-connectivity and spectrum aggregation and iii) simulation results of each of the designs, which allow to validate their features on selected scenarios, even though they are not quite similar in terms of network layout, environment, bands or traffic type. This allows however to get a consolidated MAC design prior to further MAC selection and specifications.

Next steps on the MAC definition and evaluation will completed in task T5.2 and results will be delivered in deliverable D5.2. As far as simulation results are concerned, the object of the coming deliverable is to provide means for measuring the gain of the 2 approaches on common and representative scenarios, along the KPI defined in this deliverable (see section 2.2). To achieve this objective, we have decided to focus the simulation scenarios of D5.2 on broadband communications, considering that IoT support validation is covered in this deliverable and considering that the value of Speed-5G relies in the capacity improvement enabled by carrier and spectrum aggregation for broadband applications. Even though simulations will be carried out on different system level simulators, namely NS3 and WSNet, simulations will be made comparable by specifying a set of common parameters or models.

First, in terms of simulation scenario set-up, we will define a set of parameters which will specify the following aspects (indicative list)

- Network topology and environment layout
- Traffic patterns
- Density of devices
- Propagation models (pathloss, large and small scale fading, possible penetration loss if indoor/outdoor communications are considered)
- Transceivers capabilities, in terms of transmit power, antenna gains, sensitivity, noise figure, implementation loss)

The following table gives simulations parameters considered for comparison of SPEED-5G MAC designs foreseen in D5.2. The main aim of the table is to define an initial set of common simulation parameters to be used by all partners involved in developing SPEED-5G MAC designs. It needs to be highlighted here that the table will be complemented in D5.2 by additional parameters which provide more detailed description of simulation set-ups.

Table 33: A set of main simulation parameters

Parameter	Value
Deployment types	Outdoor deployment, Indoor deployment

Network layout	Regular (Hexagonal) grid ,Irregular (Random)
Wrap-around	Yes (variable number of rings)
STA/AP height	For outdoor: 1.5m / 10 m For indoor: 1.5m / 3m
STA distribution	Random/uniform distribution WITH and WITHOUT a condition on the maximum number of UEs per BS
Path loss model	For outdoor: ITU-R UMi based model (see Note 1) For indoor: ITU-R InH (see Note 1)
Shadow fading model	For outdoor: spatially correlated lognormal shadowing with sigma = 3dB (LOS) / 4dB (NLOS) and de-correlation distance of 10m (LOS) / 13m (NLOS) (see Note 2) For indoor: spatially correlated lognormal shadowing with sigma = 3dB (LOS) / 4dB (NLOS) and de-correlation distance of 10m (LOS) / 6m (NLOS) (see Note 2)
Fast fading model	For outdoor: Considered (see Note 3) For indoor: Considered (see Note 3)
Mobility	Not considered
Traffic model	Full-buffer (saturated model), Non full-buffer (see Note 4)
Traffic type	Elastic (TCP New Reno), Non-elastic (UDP)
Application layer packet size (i.e. packet size excluding all overheads)	1500 bytes
BS density	115 per km^2 (ISD=100m), 462 per km^2 (ISD=50m), 1848 per km^2 (ISD=25m), 3850 per km^2 (ISD=17.32m) (see Note 5)
UE density	Corresponding to average number of 1) 0.5 UE per BS, 2) 1 UE per BS, 3) 2 UEs per BS, 4) 5 UEs per BS, 5) 10 UEs per BS (see Note 5)
Antenna pattern	2D Omni-directional for UE and BS
Note 1: Need for adaptation of path-loss models to model UE to UE links and BS to BS links to be investigated in D5.2. Note 2: Need for modelling of cross-correlation to be investigated in D5.2. Note 3: Details to be provided in D5.2. Note 4: Detailed parameters of non-full-buffer traffic model will be provided in D5.2. They may include bursty traffic types like FTP, as defined in [31], and Near Real Time Video, as defined in [32]. Note 5: Additional values may be considered	

As well, taking into consideration that FBMC is assumed as a possible PHY layer in SPEED-5G system, it is important to use common framework on the different simulation tools. In addition to the numerology and the different modulation and coding schemes (MCS), the following models will be defined:

- Transport block size (TrBS): taking into consideration the fact that FMC is able to provide a better spectrum utilisation, compared to CP-OFDM (e.g. LTE or Wifi), the maximum affordable transport block size will be given, for each MCS, for different resource allocation given by the scheduler (i.e. the number of subcarrier allocated to a device). This model will be provided by 2 tables, giving the TrBS for FBMC and

OFDM for equivalent efficiencies; LTE efficiencies will be taken as a reference.

- Out-of-band (OoB) emissions: As stated before in this deliverable, FBMC like other filtered multicarrier modulations are characterised by very low OoB emissions, which implies that even in asynchronous transmission on adjacent channels, the interference created by one transmission on the other is very small. In this perspective, adjacent channel interference (translated into equivalent noise addition on the adjacent channel) will be specified for FBMC modulation. Also OoB emissions will be modelled for both LTE and FBMC, when considering the entire bandwidth, corresponding to uncoordinated adjacent carriers (10 MHz and 20 MHz), taking 3GPP specifications for LTE as a baseline ([50][51]).
- Demodulation performance: Depending on the carrier configuration, adjacent channels occupancy, allocated resources, look-up-tables giving the PER versus the SINR is required. Equivalent SINR value for the whole allocated resource blocks will be calculated from the SINR estimated on every single resource blocks using conversion methods like EESM or MIESM (Exponential Effective SNIR Mapping and Mutual Information based effective SINR Mapping, respectively). This LUT is required for the FBMC and LTE for comparison purpose.

The ultimate objective of the simulation we plan for D5.2 will be to be able to compare the different eDSA capable MAC designs described in section 4 on the selected scenarios and to draw final conclusions on the better option MAC should select, given the network layout, traffic type or selected band. Such conclusions could be for instance that MAC should enable DCS-MAC for ultra-dense network in full-buffer like conditions to convey non real time constrained traffic or that the FBMC MAC would be preferred to convey bursty and time-constrained traffic when the 5GHz band is densely occupied.

5.5 Summary

This chapter presented simulation results for the MAC designs introduced in chapter 4, under synthetic and also realistic deployment scenarios. These results are a first step for the project since deliverable D5.2 will provide refined results based on common scenarios and simulation assumptions. For example, the carrier aggregation mechanism that has been evaluated assumes LTE PHY/MAC system, whereas a FBMC system using the SPEED-5G MAC is expected. Nevertheless the work reported here has allowed initial validation of the proposed MAC designs. In particular, the benchmarking results of the DCS-MAC show that the proposed design exhibits superior performance compared to WIFI systems.

6 Conclusion and future steps

This deliverable has provided a summary of the MAC protocol, considering the identified SPEED-5G MAC requirements in the defined scenarios and use cases. In the SPEED-5G project, the eDSA concept has been identified for scenarios where a large number of small cells are able to use different radio access technologies and can access multiple spectrum bands of different regimes simultaneously. For the access to shared spectrum, FBMC, which is robust to synchronization errors and very well spectrally localised, is considered as a candidate physical layer, and numerologies for IoT and broadband traffic support are presented in this deliverable.

Considering this context, the high-level MAC requirements are identified (and translated into functional entities), for the management of contention-based and non-contention-based random access control scheme to exploit (lightly) licensed spectrum and unlicensed spectrum together, and to support multi-connectivity assuming FBMC as a physical layer. Moreover, the support of several RATs and the ability to combine several carriers in both uplink and downlink are found as key aspects of the SPEED-5G MAC. With this identification of a set of SPEED-5G MAC features, the overall architecture of the MAC layer is explained, as consisting of various functional modules which are scalable and reconfigurable to coordinate the use of radio resource across HetNets and various spectrum bands in a multi-RAT capable approach. Besides a block diagram of the SPEED-5G MAC, its control and data plane interfaces, building blocks, and service access points has been defined and explained. As the MAC layer is a component of the SPEED-5G virtualized protocol stack, how the MAC layer can interact with the cRRM which maintains the strategies of capacity maximization is described. In particular, a new plane, called the *monitoring* plane, has been defined to enable sensing data and KPI reports collection at the MAC level and forwarding towards cRRM. Communication modes between the cRRM and MAC are discussed in this document. Whilst the MAC layer is assumed to be configured by the virtualized RRM algorithms, there might be the case that the SCs cannot fully exploit the virtualized architecture and the information on spectrum characteristics; for example, due to poor quality of backhaul links such information may not be available in the SCs in a timely manner. In such situation, the MAC layer would have limited support of the infrastructure in managing the interference or getting information on the available spectrum bands. In order to cover such eventuality, one of the proposed MAC designs (namely DCS-MAC) has been designed to operate in a much more autonomous manner, adapting its behaviour based on locally available information.

Based on identified SPEED-5G MAC features, the MAC algorithms are designed and explained with some preliminary results including performance evaluation on the throughput and latency on selected scenarios. Since this deliverable reports on the first version of the MAC design, the approaches described in this deliverable will be further improved during the project lifetime. In addition, sophisticated outcomes with solid system-level simulation results will be provided.

In particular, the work planned includes the investigation of eDSA usecases, revisiting and clarifying the ones identified so far or defining new ones. For example (but not restricted to this), D2D operation as an extension of infrastructure-based procedures of traffic offloading is expected to be scrutinised. This work will may result in new additions to or enhancements of existing blocks within the current MAC framework (presented in this deliverable). Additionally, the MAC interfaces will be refined and improved arriving at a specification that could complement existing Small Cell Forum specifications. From the extended list of eDSA use cases, demonstration scenarios will be selected in the light of the design and validation work done in the tasks T5.2 and T5.3 in WP5 and task T4.2 in WP4.

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APPENDIX 1

Regulatory Considerations

ETSI has defined a set of conditions devices shall respect when accessing the so-called 5GHz band, which is represented in Figure 87. We assume that only the spectrum allocated to RLAN and FWA can be used in our case, with a specific restriction for 5150-5350 MHz which can be used for indoor scenarios only.

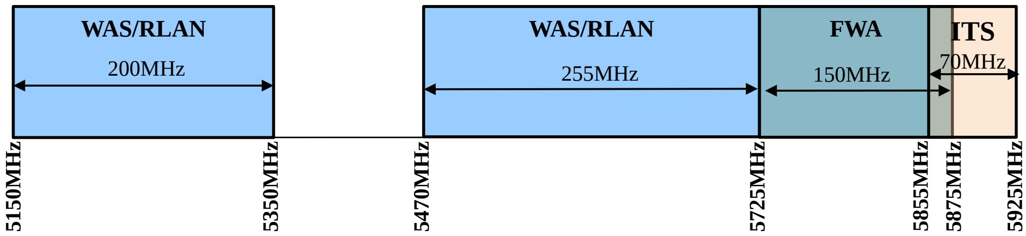

Figure 87: 5GHz band allocation (ETSI)

In terms of bandwidth, maximum transmit power, Table 34 shows the limits imposed by ETSI different channel bandwidths, knowing that a minimum 5 MHz channel is required. Note that we assume, for the sake of simplicity that the Transmit Power Control (TPC) mechanism is not be implemented, reducing the output power by a factor of 2 when channel is picked in [5250-5350] and [5470-5875] MHz.

Table 34: ETSI Transmission parameters in the 5GHz band

	freq. range (MHz)	**max mean EIRP (dBm)**	**max mean EIRP density (dBm/MHz)**	**comment**
WAS/RLAN	5150-5350	23	10	20 MHz and 40 MHz channels
	5470-5725	30	17	
FWA	5725-5875	33	23	10 MHz channels
	5725-5875	36	23	20 MHz channels
Transmit Power Control (TPC): TPC ensures an average reduction in the aggregated transmission power by at least 3 dB (5 dB for FWA) compared with the maximum permitted transmission power. TCP is not required for channels within the band 5150-5250 MHz. Without TPC, the highest permissible average EIRP (density) are reduced by 3 dB.				

As well, ETSI specifies that Dynamic Frequency Selection (DFS) is required in the bands where devices have to coexist with primary users which are radar devices; the considered bands are 5250-5350 MHz and 5470-5725 MHz. This mechanism ensures that primary users can be detected and avoided; also it provides a means to distribute the channel selection in a near-uniform manner in the band. The implementation of DFS is considered as beyond the scope of this contribution, which focuses on how the access is handled once the channel is selected.

Together with DFS, a Listen-Before-Talk (LBT) mechanism is mandatory, to assess whether the channel is occupied or not. ETSI describes two modes which are “frame based equipment” and “load based equipment”; assumption is made that we use the first option in this work. The clear channel assessment is done using an energy detector and shall respect a minimum duration. Table 35 gives details on how LBT procedure should be applied and Figure 88 depicts an example of timing for the “frame based equipment” mode. For further details on DFS and LBT, the interesting reader can refer to [5].

Table 35: LBT procedure parameters

parameter	requirement	comment
Clear Channel Assessment time	Minimum 18 µs	
Channel Occupancy time	Minimum 1 ms, maximum10 ms	
Idle period	Minimum 5% of channel occupancy time	
Fixed frame period	Equals to Channel Occupancy time + Idle Period	
Short control signaling transmission time	Maximum duty cycle of 5% within an observation period of 50ms	Part of Channel occupancy time
CCA Energy detection threshold **(0 dBi antenna)**	If EIRP=23dBm at transmitter Threshold ≤ -73 dBm/MHz Otherwise (for a different transmit power level denoted PH) Threshold = -73(dBm/MHz) + 23(dBm) – PH(dBm)	For WAS/RLAN

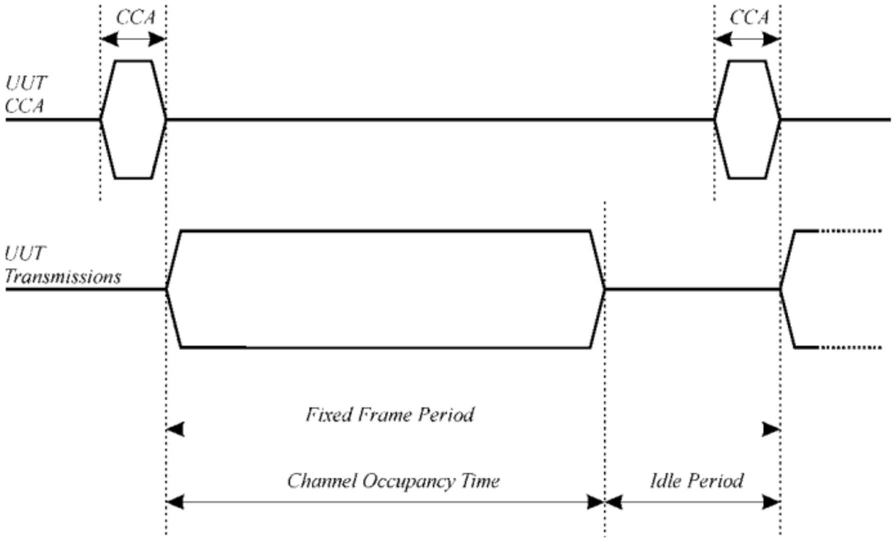

Figure 88: LBT timing example [5]

Clearly, the LBT mechanism makes it possible to turn this regulatory rule into frame-based TDD access where the small cell can trigger the scheduling of a frame composed of uplink and downlink slots upon the detection of an idle channel. Depending whether the channel is idle or not, the frame will be sent or refrained. The channel occupancy time, as exposed in Table 35 can vary from 1ms to 10ms; the frame length can be mapped on this value which is a typical RRM decision depending on the interference level and the load to be sent on the unlicensed spectrum.

APPENDIX 2

Traffic patterns and device classes

In this section, traffic patterns derived from 3GPP cellular-IoT (C-IoT) are presented followed by the device classes defined to meet the traffic applications.

Traffic patterns - In order to determine the traffic patterns that govern the MAC design, contributions of the C-IoT Working Group in GERAN have been extensively analysed. For instance, four different application traffic models are described to reflect the traffic characteristics of applications expected to be supported and which are the baseline of performance assessment of the proposed PHY/MAC specifications. For details on the different modes, see [14]. These modes are:

- UL: Mobile Autonomous Reporting (MAR) exception report (ER), e.g., alarms,
- UL: MAR periodic report (PR),
- DL: Network command (NC),
- DL: Software update / reconfiguration model.

In the following, we consider only the first three. The characteristics of the considered traffic in the uplink and downlink directions are summarized in Table 36. For system capacity evaluations, MAR periodic reports and network commands are considered. In this traffic model, the split of devices between MAR periodic and network command is MAR periodic (80%) and network command (20%). The uplink traffic consists of periodic reports, exception reports and the responses to the network commands, while the downlink traffic consists of network commands and the acknowledgments for PRs and ERs.

Table 36: Uplink and Downlink Traffic patterns

	events	**frequency (reports per device)**	**device percentage**	**payload**	**latency**
uplink traffic	MAR periodic reports (PRs) (e.g., gas/water/electric smart metering reports, Smart agriculture Smart environment) (80% of devices)	1 per day 1 per 2 hours 1 per hour 1 per 30 min	40 % 40 % 15 % 5 %	20-200 bytes	Not critical (a few minutes)
	MAR exception reports (ERs) (e.g., alarm detectors, tamper notifications, power failure notification from smart meters)	Every few months or every years	100 %	20 bytes	10 s
	Response to NCs	same as NCs	50 % of NCs	20-200 bytes	5% resp. <1s
downlink traffic	Network commands (NCs) (e.g., command to switch on the lights, trigger the device to send an uplink report) (20 % of devices)	1 per day 1 per 2 hours 1 per hour 1 per 30 min	40 % 40 % 15 % 5 %	20 bytes	Depends on command (from 10min to 1 sec)
	Ack for PRs	same as PRs	50 % of PRs	0 bytes	
	Ack for ERs	same as ERs	100 % of ERs	0 bytes	

The periodic reporting mode pertains to sensor-based devices, which are expected to send periodic measurement reports. Periods can vary from a few minutes up to 1 day. 3GPP GERAN considers a minimum period of 30 minutes [14]; 3GPP RAN considers a minimum period of 5 minutes (1 min optional). Typical examples of such devices are environmental monitoring sensors (1 packet up to each 15 minutes) or gas smart metering (1 packet every 12h). Generally speaking the lower is the transmission rate the more stringent is the energy constraint, leading to maximum expected lifetime of 10 years on a 5Wh battery. Assumption is made that 50 % of PRs require an acknowledgment.

Compared to PR, exception reports are event-driven packets emissions on the device side. ERs typically occur when the value of the sensed physical quantity exceeds a given threshold, implying a kind of alert-type emission. Provided this type of report corresponds to a form of extraordinary behaviour, assumption is made that ER require an acknowledgment. In addition, GERAN includes a maximum latency ERs have to comply with. The maximum latency value is set to 10s.

According to [14], 20% of the traffic can be for network commands. These DL packets are short packets (20 bytes payload) sent with the same packet generation rate compared to PRs (from 1h to a day). Assumption is made that 50% of NCs induce a response on the device side. NC response is a packet of the same length order than a PR. The latency to response to the NC is a critical point, 5 % of the devices are assumed to respond with a delay less than 1 s.

Device classes - Depending on the applications and requirements of IoT traffic, the devices are classified into 3 main categories denoted as class 0 to class 2 ($\mathrm{C_p}, \mathrm{p} = 0,1,2$). Table 37 summarizes the characteristics and communication capabilities for each class.

Table 37: IoT device classes

	characteristics
class 0 device	Uplink traffic (Periodic reports) Packet arrival rate λ_p (Reporting interval T_RI) Number of repetitions = [0 – 2] (default 1)
class 1 device	Uplink traffic (Periodic and exception reports)with an Ack. Packet arrival rateλ_p (Reporting interval T_RI) Ack timeout = 2 superframe durations Max number of retransmission = 3
class 2 device	Uplink traffic (Periodic and exception reports, Response for NC) Downlink traffic (NCs) Packet arrival rateλ_p (Reporting interval T_RI) Ack timeout, Max number of retransmission Wake-up Time T_w Response for NC : yes or no (50 % in TR 45.820) Max latency for sending response: 1s (5%), 1 minute (20%), 10 minutes (75%)

All IoT devices are expected to perform periodic reporting. Periodic reporting can be modeled by a Poisson arrival process with arrival rate $\lambda_\mathrm{p} = 1/T_\mathrm{RI}$, where T_RI denotes the duration of the reporting interval. This reporting interval ranges typically from few minutes to 1 day and must be specified for each device. Exception reporting is supported by class 1 and class 2 devices. Meanwhile class 2 devices are expected to receive network commands.

The devices in class 0 support only uplink traffic. They send periodic reports to the SC without requiring any acknowledgment. This type of device is not aware if a collision occurs or if the packet is correctly received. Therefore the device can transmit the packet with redundancy in order to increase the probability of successful receiving the reports. The number of packet repetitions can be set between 0 and 2 with a default value of 1.

The devices in class 1 perform periodic and exception reporting. This class of devices requires an acknowledgement of the transmitted packet. If no acknowledgment is received within the specified period (Ack timeout), the packet is retransmitted by the device until successful transmission (Ack received) or when a maximum number of retransmission is reached.

Class 2 devices are more critical in IoT network. This type of device is supposed to be able to receive network command from the SC. Provided IoT devices are particularly constrained from a power consumption perspective, they are in a sleeping mode most of the time. This means that the radio is switched off most of time, implying that the management of the downlink is particularly tricky. To overcome this issue, we propose that the device wakes up periodically for a short period of time T_W , then listens to beacon to determine if there is any traffic (network command) from the SC. If a response to the network command is required, the maximum latency for sending response to NC must be specified for such device. The wake-up time and the latency are in general highly related to each other, the lower is the latency to sending the response, the shorter is the wake-up time of the device.

APPENDIX 3

Discussion on power consumption modes

In this section, we discuss the power consumption modes of IoT devices which are energy constrained. Generally, power consumption depends on many factors such as the transmission time, transmit power level, receiving time, sleep mode and idle mode duration. Since most IoT devices are assumed to have a long battery life which may ranges from hours to 10 years, a low power consumption model has to be specified for each device.

Four operation modes can be distinguished: Tx state, Rx state, idle state and sleep state. The Tx state is the most energy consuming one, in which the microcontroller is running and the radio is in Tx mode. In the Rx state, the microcontroller is running and the radio is in Rx mode. The Rx state is critical since the device spends a lot of time to listen to the medium. In idle state, the microcontroller is running but the radio is off. Meanwhile, in sleeping state, the microcontroller is in sleep mode and the radio is off.

Power consumption in downlink direction is more critical than in uplink direction. Indeed in downlink direction, the challenge is to transmit network command from the SC to some devices without requiring that the devices continuously listen to the channel. The preamble sampling technique is proposed in this context (see section 4.1.3.3), where the device regularly listens to the radio channel for a short duration to check if it has a notification to receive.

A key question that arises is: which power consumption modes will be more efficient? Two cases can be distinguished: 1) When the device is always synchronized with the beacon and listen to all beacons or 2) when the device is in sleeping mode for most of the time (multiple of the superframes) and then wakes up asynchronously, listen to the channel and synchronizes with the beacon?

In the first case, it is assumed that the device wakes up and listens to all beacons. The ratio of listen period to superframe period is equal to 1.2/ 614.4 = 1/512. Note that, the device clock may have drifted so the device wakes up too late. Therefore, to guarantee that the device is well synchronized with the beacon, a guard period just before the beacon period has to be considered taking into account a possible drift. For simplicity, this guard period is not considered in the analysis. (A maximum guard time of 100µs can be considered).

In the second case, the device does not listen to all beacon frames, it listens to the medium at its wake-up period, then synchronizes with the beacon. The time required to listen to the medium is critical and the worst case arises when the device wakes up and the beacon has been just sent, therefore the device must listen to the medium for at least one superframe duration. The best case scenario is obviously that the device wakes up just before the beacon. The baseline listen time we consider in this analysis is the average listen time, which is of half superframe duration.

Let T_{th}be the wake-up period threshold, and T_{sensing} the duration required to listen to the medium and to synchronize on a beacon; the ratio of listening duration over wake-up period corresponds to $T_{\mathrm{sensing}}/T_{\mathrm{th}}$. In order find the minimum wake-up period that leads to a better energy efficiency compared to synchronize on all the beacons, one should determine T_{th}which provides the same power consumption efficiency of the two considered cases, the ratios must be equal: $T_{\mathrm{sensing}}/T_{\mathrm{th}} = 1/512$, it allows that the wake-up period threshold is equal to $T_{\mathrm{th}} = 314.5\text{ s} = 5.24\text{min}$ and $T_{\mathrm{th}} = 157.28\text{ s} = 2.6\text{min}$ in the case of worst-case sensing and reasonable case sensing, respectively. Therefore if the wake-up period of the device is less than the threshold ($T_{\mathrm{th}} = 5\text{ min } or \text{ } 2.5\text{ min}$),it is more efficient to the device to synchronize and listen to all beacons. Otherwise, the wake-up (sleeping) period of the device may be adjusted depending on traffic pattern.

The device can also exchange sleep schedule and next wake-up period with the SC. This sampling schedule can be for example embedded into the network command response or in an Ack. The SC must in this case maintain a table of the device addresses and their corresponding wake-up periods.

Using this table, the SC starts to send the notification just before the wake-up period by taking into considerations the clock drifts, reducing the number of NC notifications repetitions.

The power state transition for different IoT devices can be summarized as follows:

If a device is expecting to receive network command and must listen to all beacon frames, then the device shall wake up for a guard time prior to the beacon period in every superframe to receive the beacon. Then the device may go into sleep mode and wakes up prior to the start of the reserved resource indicated in the beacon to receive the NC. After receiving the NC, the device may go to sleep mode again. If a response to NC is required, then the device shall wake up again prior to the reserved resource indicted to send the response.

If the device is in sleep mode for most of the time, it shall wake up at least one superframe and shall synchronize to the beacon during this superframe. If it has a notification to receive NC (with a countdown field set to the number of remaining superframes before sending the NC), the device may go into sleep state and shall reduce the value of the countdown for each superframe duration. If this value reaches zero, the device shall wake-up prior to resynchronize to the beacon and receive NC.