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Preliminary report on iJOIN MAC/RRM state-of-the-art, requirements, and scenarios

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Abstract

This report presents an overview of the activities carried out by Work Package 3 (WP3) during the first six months of iJOIN project. These activities include a detailed state-of-art analysis of the main MAC (Medium Access Control) and RRM (Radio Resource Management) solutions which can be used both for the radio access and the backhaul of a dense small-cell network. Additionally, a state-of-art for cloud RAN (Radio Access Network) and cloud platforms is also provided. Finally, the candidate technologies for MAC and RRM which will be developed in future stages of the project are also introduced. A consolidated list of the assumptions required by these candidate technologies is obtained as input to WP5.

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Abbreviations

3GPP	3rd Generation Partnership Project
AM	Acknowledged Mode
AMC	Adaptive Modulation and Coding
API	Application Platform Interface
ARQ	Automatic Repeat reQuest
BCCH	Broadcast Control Channel
BCH	Broadcast Channel
BN	Backhaul Node
BS	Base Station
CA	Carrier Aggregation
CAPEX	Capital Expenditures
CC	Component Carrier
CCA	Common Channel Assignment
CCCH	Common Control Channel
CDMA	Code Division Multiple Access
CoMP	Coordinated Multi Point
CPRI	Common Public Radio Interface
C-RAN	Cloud - Radio Access Network
CQI	Channel Quality Indicator
CS	Common Scenario
CSI	Channel State Information
CT	Candidate Technology
CU	Central Unit
CWDM	Coarse Wavelength Division Multiplexing
DAS	Distributed Antenna System
DL	Downlink
DL-SCH	Downlink Shared Channel
DRX	Discontinuous Reception
DSL	Digital Subscriber Line
DTX	Discontinuous Transmission
eICIC	Enhanced Inter-Cell Interference Control
EM	Element Management
eNB	Evolved Node B
EPC	Evolved Packet Core
EPS	Evolved Packet System
E-UTRA	Evolved UMTS Terrestrial Radio Access
E-UTRAN	E-UTRA Network
FAPI	Femto Application Platform Interface
FDD	Frequency Division Duplex
FFT	Fast Fourier Transform
FSO	Free-Space Optical
GPON	Gigabit Passive Optical Network
GSM	Global System for Mobile Communications
HARQ	Hybrid ARQ

HetNet	Heterogeneous Network
HSDPA	High Speed Downlink Packet Access
HSPA	High Speed Packet Access
IA	Interference Alignment
IaaS	Infrastructure as a Service
ICIC	Inter-Cell Interference Control
iJOIN	Interworking and JOINt Design of an Open Access and Backhaul Network Architecture for Small Cells based on Cloud Networks
IMT	International Mobile Telecommunications
iNC	iJOIN Network Controller
INP	In-Network-Processing
IP	Internet Protocol
IR	Incremental Redundancy
iSC	iJOIN Small Cell
IT	Information Technology
iTN	iJOIN Transport Node
ITU-R	International Telecommunication Union – Radio
LA	Link Adaptation
LCG	Link Contention Graph
LoS	Line of Sight
LTE	Long Term Evolution
MAC	Medium Access Control
MCCH	Multicast Control Channel
MCH	Multicast Channel
MCS	Modulation and Coding Scheme
MIMO	Multiple Input Multiple Output
MME	Mobility Management Entity
MTCH	Multicast Traffic Channel
NAS	Non-Access Stratum
NCG	Node Contention Graph
NE	Network Element
NM	Network Management
OBSAI	Open Base Station Architecture Initiative
OFDMA	Orthogonal Frequency Multiple Access
OPEX	Operational Expenditures
OSS	Operational Support Systems
PaaS	Platform as a Service
PCCH	Paging Control Channel
PCell	Primary Cell
PCH	Paging Channel
PDCP	Packet Data Convergence Protocol
PDU	Packet Data Unit
PON	Passive Optical Network
PoP	Point-of-Presence
PPI	Power Preference Indication
PRB	Physical Resource Block

PS	Packet Scheduler
PUCCH	Physical Uplink Control Channel
QCI	QoS Class Indication
QoS	Quality of Service
RACH	Random Access Channel
RAN	Radio Access Network
RANaaS	RAN as a Service
RAP	Radio Access Point
RAT	Radio Access Technology
RB	Radio Bearer
RF	Radio Frequency
RLC	Radio Link Control
RNC	Radio Network Controller
ROHC	Robust Header Compression
RRC	Radio Resource Control
RRH	Remote Radio Head
RRM	Radio Resource Management
SaaS	Software as a Service
SCell	Secondary Cell
SDU	Service Data Unit
S-GW	Serving Gateway
SINR	Signal to Interference and Noise Ratio
SON	Self-Organizing Networks
TDD	Time Division Duplex
TM	Transparent Mode
TTI	Transmission Time Interval
TTT	Time to Trigger
UE	User Equipment
UL	Uplink
UM	Unacknowledged Mode
UMTS	Universal Mobile Telecommunication System
VCA	Varying Channel Assignment
VoIP	Voice over IP
Wi-Fi	Wireless Fidelity
WiMax	Worldwide Interoperability for Microwave Access
WMS	Wireless Mesh Networks
WP	Work Package

1 Introduction

Future mobile networks need to cope with exceptionally greater traffic volumes driven by the increasing use of high data rate applications, such as video streaming or video games, in smartphones and other new mobile devices. In order to handle this exponential traffic increase, the use of very dense, low power, small cell networks with a high spatial reuse is the most promising option. Nevertheless, this approach faces several challenges: on the one hand, small cell deployments will require a high degree of coordination due to strong inter-cell interference. On the other, the connection of the small cells to the core network will be performed in many cases using a heterogeneous backhaul, but so far access and backhaul networks are individually designed and therefore not optimised jointly.

To tackle these challenges, the iJOIN project aims at the design of an enhanced mobile network architecture based on the following two concepts: first, the introduction of the RAN-as-a-Service (RANaaS) concept to centralize the Radio Access Network (RAN) functionality through an open Information Technology (IT) platform based on a cloud infrastructure. This centralization allows handling the interference of the network from a global perspective, leading to the proposal of optimised solutions that improve the energy efficiency and the total throughput of the network. Second, iJOIN aims for a joint design of access and backhaul, integrating in this design small-cells, heterogeneous backhaul and centralised processing. Within this frame, the scope of Work Package 3 (WP3) of iJOIN is the proposal of Medium Access Control (MAC) / Radio Resource Management (RRM) solutions for the backhaul and access networks. These solutions will be based on a holistic backhaul and access design for very dense small-cell networks, as well as a leveraging of the RANaaS concept for improved flexibility and exploitation of the cloud resources.

In this report, the state-of-the-art of the main topics involved in the MAC/RRM design of iJOIN is presented. These topics are described in detail in Section 3, which includes an introduction to the MAC aspects of Long Term Evolution (LTE), a thorough analysis of the radio access and backhaul solutions that can be applied to a very dense network with high interference level and non-ideal backhaul, and an overview of the main characteristics of cloud-RAN and cloud platforms. The other topic covered in this report is a presentation of the MAC/RRM Candidate Technologies (CTs) that will be developed in the project. For each CT, its description, assumptions, requirements and objectives is given. Additionally, each CT is mapped to the use cases defined in WP5, specifying to which use case each CT can be applied. These use cases are stadium, square, wide-area continuous coverage and indoor. A detailed description of each use case can be found in the IR5.1 document.

2 Executive Summary

This report describes the main activities carried out by the WP3 during the first six months of the iJOIN project. The main objective of this report is to present the state of the art literature for the MAC/RRM design of backhaul and access networks and to provide an overview of the principal candidate technologies and solutions which will be explored by WP3 in the next stages of the project. The report is organized as follows:

In Section 3, the state of the art for 3GPP LTE releases 10/11/12, MAC for radio access and backhaul, cloud RAN and cloud platforms is presented. Section 3.1 describes the general concepts of LTE from MAC to RRC, explaining the protocol layers that perform these functionalities. Section 3.1.1 focuses completely on LTE release 10, detailing the functions located in the eNB and the description of the LTE air interface protocol stack, specifically the MAC, RLC and PDCP layers. Section 3.1.2 explains the main improvements introduced in release 11 of LTE regarding carrier aggregation, coordinated multi-point and mobility in heterogeneous network. The small cell enhancements introduced in LTE release 12 to increase the capacity of the network are analysed in Section 3.1.3.

Section 3.2 focuses on the state of the art for MAC/RRM at the radio access, detailing the main RRM schemes that can be used to mitigate the inter-cell interference in dense small cell deployments, and therefore, to lead to energy savings and improved throughput. These schemes span carrier aggregation, which allows using up to five different component carriers to obtain up to an aggregated 100MHz bandwidth; cooperative transmission, where several entities cooperate to simultaneously transmit or receive data to or from a mobile user; link adaptation and multi-user scheduling, which consider the specific channel suffered by each terminal to exploit multi-user diversity and transmit to terminals with higher SINRs; inter-cell interference coordination mechanisms operating in the frequency and spatial domain and that perform a dynamic management of the available power and bandwidth; interference mitigation techniques, such as dirty paper coding or interference alignment, that exploit a-priori knowledge of the interfering user’s messages to cancel the interference at each served user; and optimal resource allocation, which uses complex optimization algorithms to maximize some performance indicator in an adaptive fashion.

Regarding the backhaul network, the main wired and wireless solutions are analysed in Section 3.3. First, wired backhaul is presented in Section 3.3.1, where the main characteristics of copper and fibre are described. Both solutions present cost problems, which causes the introduction of wireless backhaul in Section 3.3.2. These wireless solutions span microwave radio links using high directional antennas; Wi-Fi deployments using smart mesh techniques together with adaptive antenna arrays; free space optical backhaul that uses non-guided optical links to achieve high bandwidth; satellite backhaul, which can be used in remote locations and millimetre wave radio in the ≥60 GHz band. This last technology has unique characteristics since it provides high bandwidth together with excellent immunity to interference, high security and reuse of frequency. Section 3.3.3 explains the fundamental topologies that can be found for the backhaul, namely point-to-point, point-to-multipoint and mesh. The main challenges that must be addressed when designing the backhaul (channel assignment, QoS support, routing, load balancing…) are summarized in Section 3.3.4, while the solution frameworks for these challenges are depicted in Section 3.3.5.

Section 3.4 describes the state of the art for cloud RAN. In cloud RAN, some of the tasks performed generally at the base stations are shifted to a cloud data centre. Thanks to this, the resource provisioning can be done considering the overall sum load of the whole network, which increases the efficiency of the system. The main drawback is the necessity of high capacity links to connect the radio access points to the data centre. Sections 3.4.1 lists the existing cloud RAN architectures developed so far by Alcatel Lucent, China Mobile, ZTE, Huawei, NSN and IBM. Section 3.4.2 describes the existing protocols and APIs that can be used to connect the radio access points to the cloud data centre, while the function split between these entities is outlined in Section 3.4.3. Section 3.5 is devoted to the state of the art for cloud platforms, focusing specially in its possible application for the iJOIN project. For this case, the envisioned service model is because this is the best way to build a system with guarantees on execution performance.

Section 4 discusses the nine different MAC/RRM CTs. For each CT, its description, assumptions, requirements and objectives within the scope of iJOIN are described. The first CT is “Joint path selection and radio resource scheduling”. This CT aims at the joint, locally centralized execution of the routing and resource scheduling algorithms to increase the efficiency of the network (Section 4.1). The CT “Partly decentralized mechanisms for joint RAN and backhaul optimization in dense small cell deployments”, described in Section 4.2, investigates the relationships between RAN capacity, cell load, resource scheduling and backhaul capacity to propose innovative cell selection mechanisms. The energy efficiency of the system is studied in CT 3, named “Energy-efficient MAC/RRM at access and backhaul” (Section 4.3). Section 4.4 describes CT 4 “Computation complexity and semi-deterministic scheduling”. This CT uses the computational resources of cloud platforms to perform part of the scheduling algorithms in a centralized fashion thanks to the global knowledge of the network that can be achieved through this centralization. CT 5 analyses cooperative solutions to perform effective inter cell interference coordination techniques using the centralization provided by RANaaS (Section 4.5). Utilization efficiency is addressed in CT 6 (Section 4.6), where new metrics to capture the utilization efficiency of the network are proposed and the potential benefit of RANaaS and joint access/backhaul regarding this efficiency is investigated. CT 7, “Radio Resource Management for Scalable Multi-Point Turbo Detection”, relies on improving the detection quality of the users to increase the (aggregated) uplink of the network and to improve spectrum utilisation (Section 4.7). In Section 4.8 the CT “In-Network-Processing for RX cooperation” is described. The main objective of this CT is to increase the area throughput and to decrease the transmit power consumption. The last CT is “Joint Backhaul and radio resource allocation Rate adaptive strategies for Optimized Uplink Transmissions”. This CT proposes techniques that make the active users provide a low rate feedback of their channel conditions. With this information, the radio resource assignments can be done as per the users demands.

Section 5 summarizes the mapping of WP3 CT to the different use cases considered in iJOIN as defined in WP5 (stadium, square, wide-area continuous coverage and indoor). Finally, Section 6 presents the consolidated WP3 assumptions and requirements for all CTs.

3 State of the Art

The deployment of very dense small-cell networks is the most promising strategy to increase the capacity and throughput offered by mobile systems. Nevertheless, this approach faces several challenges related to the interference management at the radio access and the design of a backhaul network where possible bandwidth constraints must be taken into account. The solutions proposed by the iJOIN project to these challenges are based on a centralized processing of resource assignments in a cloud platform and on a joint design of access and backhaul to be tackle the limitations which may be imposed in both networks. In this section, an in-depth analysis of the state-of-the-art regarding LTE, MAC strategies, backhaul design and cloud platforms is provided. These technologies form the basis on which the solutions proposed in iJOIN rely.

3.1 MAC/RRC State of the Art of 3GPP LTE Rel. 10/11/12

3GPP LTE (originally Long-Term Evolution) is, as the name suggests, an evolutionary enhancement of the 3GPP Universal Mobile Telecommunication System (UMTS). The term “LTE” loosely describes a set of specifications which can be mapped to core network enhancements in the Evolved Packet Core (EPC) and to radio access enhancements in the Evolved UMTS Terrestrial Radio Access (E-UTRA). The whole system including EPC, E-UTRAN and User Equipment (UE) is denoted as Evolved Packet System (EPS).

Although many new technologies have been introduced in LTE such as OFDMA (Orthogonal Frequency Multiple Access) as multiple access techniques, many existing features and principles have been inherited from UMTS. One specific example is the radio access protocol stack, which has the same structure as in UMTS, but with slightly different functions of the individual protocols.

In this sense, the main architectural difference to UMTS before HSDPA/HSPA is the termination of the Radio Resource Control (RRC) protocol, the Radio Link Control (RLC) protocol, and the Packet Data Convergence Protocol (PDCP) in the evolved Node B (eNB) instead in the Radio Network Controller (RNC). In the protocol stack, some functions such as packet re-ordering were re-located from RLC to PDCP, along with some other smaller modifications.

Figure 3-1 provides an overview of approximate dates of 3GPP releases up to LTE Rel. 10. It can be observed that the pace of releases increases with the introduction of LTE. LTE Rel. 10 is officially recognized as an ITU-R IMT-Advanced technology, which is the reason why it is also denoted as LTE-Advanced by 3GPP.

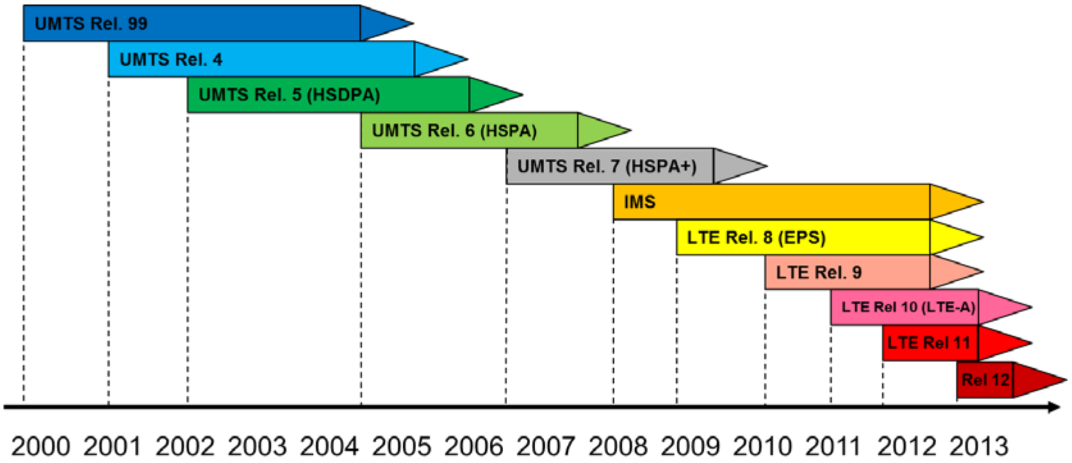


Figure 3-1: 3GPP releases until LTE Rel. 10

3.1.1 General Concepts (Release 10)

This section describes general concepts of LTE from MAC to RRC. It assumes LTE Rel. 10 as baseline. It is further assumed that the reader is familiar with general concepts of 3GPP LTE such as the Quality of Service (QoS) framework and the overall EPS architecture [1] [2].

The following functions are located in the eNB [3]:

- Radio Resource Management (RRM), including Radio Bearer (RB) control, radio admission control, connection mobility control, and dynamic allocation of resources to UEs in both uplink and downlink (scheduling);
- IP header compression and encryption of user data stream;
- Routing of user plane data towards Serving Gateway (S-GW);
- Scheduling and transmission of paging messages and broadcast information;
- Measurement and measurement reporting configuration for mobility and scheduling;

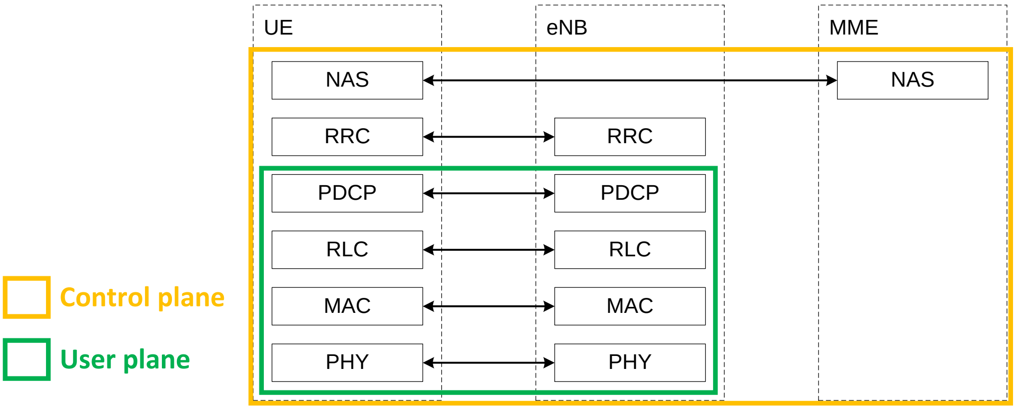


Figure 3-2: LTE control and user plane protocol stack [3]

Figure 3-2 shows an overview of the LTE air interface protocol stack. The user plane comprises PHY, MAC, RLC and PDCP. Additionally, the control plane includes RRC and Non-Access Stratum (NAS) signalling which terminates in the Mobility Management Entity (MME) in the EPC. Since NAS is terminated in the EPC it is not in scope of iJOIN and it will not be analysed in this document.

The different protocol layers are responsible for the following functionalities [3]:

RRC (Radio Resource Control) [4]:

- Broadcast of system information and paging;
- Establishment, maintenance and release of an RRC connection between the UE and E-UTRAN including:
    - Allocation of temporary identifiers between UE and E-UTRAN;
    - Configuration of signalling RBs for RRC connection;
    - Security functions including key management;
    - Establishment, configuration, maintenance and release of point to point RBs;
- Mobility functions including:
    - UE measurement reporting for inter-cell and inter-RAT mobility;
    - Handover and UE cell selection and reselection;
    - Context transfer at handover.
- QoS management functions;
- UE measurement reporting and control of the reporting;

PDCP (Packet Data Convergence Protocol) [5]:

- Header compression and decompression for Voice over IP (VoIP) by implementing ROHC (RObust Header Compression);

- Transfer of user data, in-sequence delivery and duplicate detection in case of RLC AM (Acknowledged Mode) re-establishment (e.g. in case of hand-over);
- Retransmission of PDCP Service Data Units (SDUs) at handover for RLC AM;
- Ciphering and deciphering of user plane data, as well as additionally integrity protection for control plane data.

RLC (Radio Link Control) [6]:

- Support of Transparent Mode (TM), Unacknowledged Mode (UM) and Acknowledged Mode (AM). UM supports in-sequence delivery of data, while AM additionally supports error correction by means of Automatic Repeat-reQuest (ARQ).
- Concatenation, (re-)segmentation and reassembly of RLC SDUs for UM and AM data transfer;
- Reordering and duplicate detection of RLC data PDUs for UM and AM data transfer;

MAC (Medium Access Control) [7]:

- Mapping between logical channels and transport channels and multiplexing/demultiplexing of MAC SDUs belonging to one or different logical channels on transport channels;
- Scheduling of information reporting from UEs, e.g. for channel measurements;
- Error correction through Hybrid ARQ (HARQ). LTE implements asynchronous N-stop-and-wait HARQ with Incremental Redundancy (IR), thus allowing to adapt the format of retransmissions to the current channel condition;
- Priority handling by means of dynamic scheduling (QoS scheduling), based on QoS Class Indications (QCIs) which are associated with each RB;
- Transport format selection by means of Adaptive Modulation and Coding (AMC).

Figure 3-3 gives an overview of the protocol stack along with some functions assigned to the different layers. The figure also shows the scope of the RBs (which terminate above PDCP), logical channels, Common Control Channel (CCCH), Broadcast Control Channel (BCCH), Paging Control Channel (PCCH), Multicast Control Channel (MCCH) and Multicast Traffic Channel (MTCH), which terminate at RLC, and transport channels Downlink Shared Channel (DL-SCH), Broadcast Channel (BCH), Paging Channel (PCH), and Multicast Channel (MCH), which terminate below MAC.

Note that in case of Carrier Aggregation (CA), two or more Component Carriers (CCs) are aggregated in order to support wider transmission bandwidths up to 100 MHz (a description of CA can be found in section 3.2). A UE may simultaneously receive or transmit on one or multiple CCs, and a Rel. 10 UE can simultaneously receive and/or transmit on multiple CCs corresponding to multiple serving cells. It is furthermore possible to configure a UE to aggregate a different number of CCs originating from the same eNB and of possibly different bandwidths in the uplink (UL) and the downlink (DL). In this case, one transmission chain (from MAC to PDCP) would exist for each CC in parallel. This basic set of features for CA is provided in Rel. 10. Additional ones have been included in Rel. 11 and will be further refined in Rel. 12.

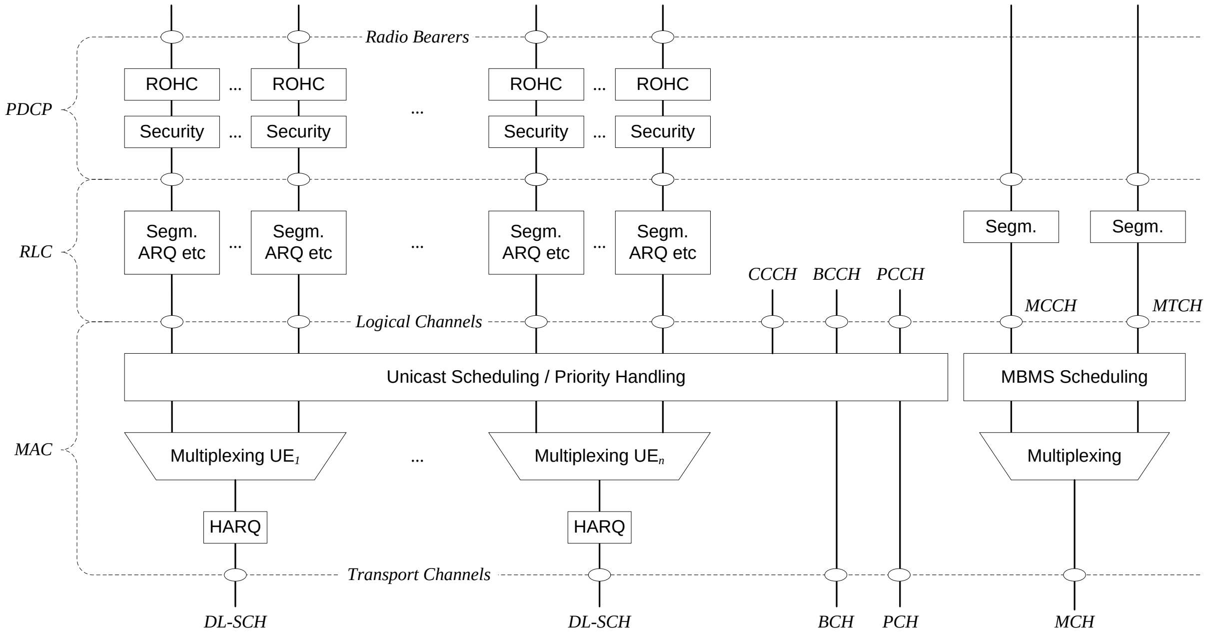


Figure 3-3: Layer 2 structure for downlink [1]

From the above description of LTE Rel. 10 and as it is shown in Figure 3-4, RRM functions such as RB control, Inter-Cell Interference Control (ICIC), radio admission control and resource allocation/packet scheduling are located in the eNB, whereas functions related to mobility management and idle mode are located in the EPC, specifically in the MME.

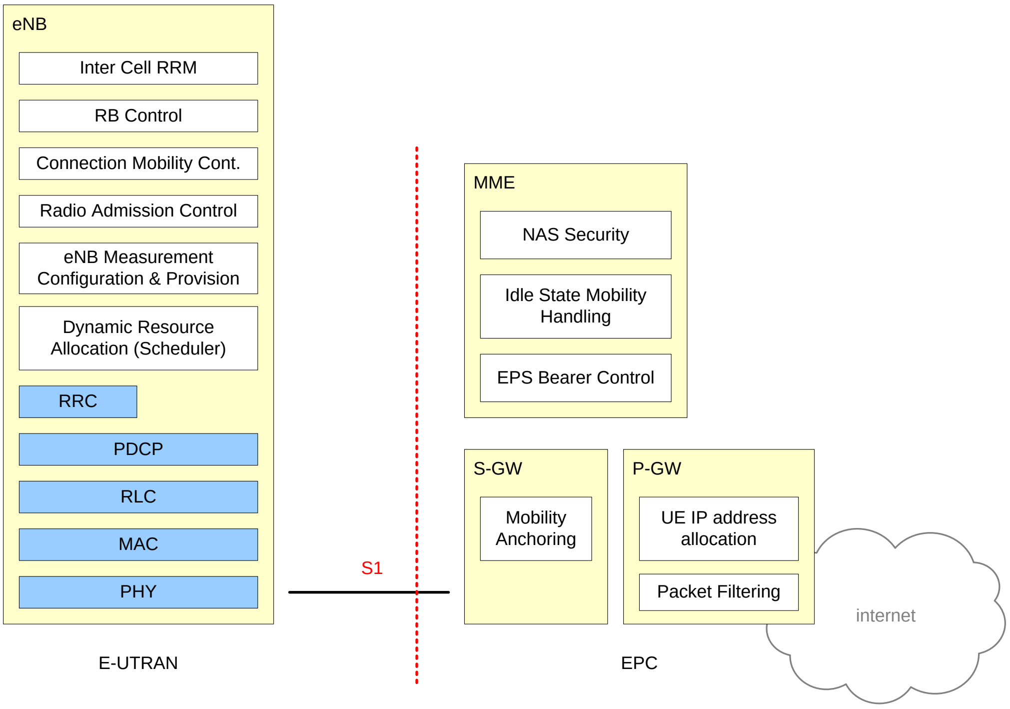


Figure 3-4: Functional split between E.UTRAN and EPC [1]

3.1.2 Release 11

LTE Rel. 11 has a number of enhancements mainly targeted to complete crucial features of LTE-Advanced which have not been studied in detail in Rel. 10 due to lack of time. An overview of Rel. 11 work and study items can be found in [8]. An overview of the latest LTE RAN Rel. 11 specification is provided in [9].

A large share of the work items in Rel. 11 covers various enhancements to CA, especially on inter-band CA, such that an UE can be served on different bands and potentially also from different cells, where one cell is the Primary Cell (PCell), which is also responsible for radio resource control and management, and the rest of cells are the Secondary Cells (SCells), which can serve a number of component carriers each. Figure 3-5 shows two example scenarios which use inter-band CA; in the first case, the SCells are co-located (at the same site) as the PCells. In the second case, a central site is complemented with a number of Remote Radio Heads (RRHs) for capacity extension.

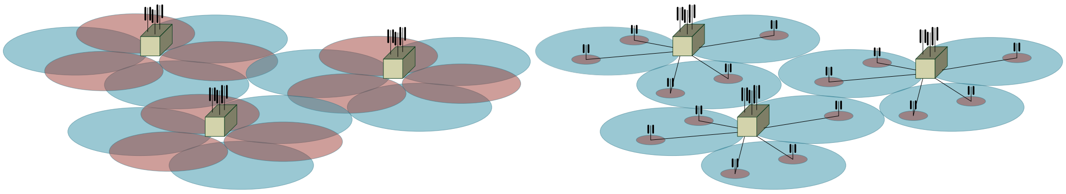


Figure 3-5: Two inter-band carrier aggregation scenarios with co-located cells (left) and RRHs (right) [9]

In order to enable this, management functionalities and key performance indicators have been identified. Furthermore, the issue of different timing advance values for different CCs, especially in different bands, has been addressed. Inter-band CA is studied in [10].

A further topic was Coordinated Multi-Point (CoMP) operation, which has been studied in [11]. In this study item, definitions of CoMP categories (join processing and coordinated scheduling/beamforming) have been introduced: in joint processing data is simultaneously transmitted from multiple points to improve the signal quality or data throughput, while in coordinated scheduling/beamforming data is transmitted from one point, but in a coordinated way with other transmission points. An example of a CoMP scenario is depicted in Figure 3-6.

Cooperation is performed in a *CoMP cooperating set*, while joint transmission is executed in a *CoMP transmission point set*, being the latter a subset of the first. *CoMP measurement sets* define points (usually UEs) which provide channel state and further link-level statistical information towards the CoMP cooperating or transmission point set. Figure 3-6 shows a possible scenario for CoMP operation with central eNB and a number of RRHs which all together form the CoMP cooperating set. In [9], a short section for downlink and uplink CoMP has been introduced, which cover transmission of Channel State Information (CSI) measurements to different transmission points.

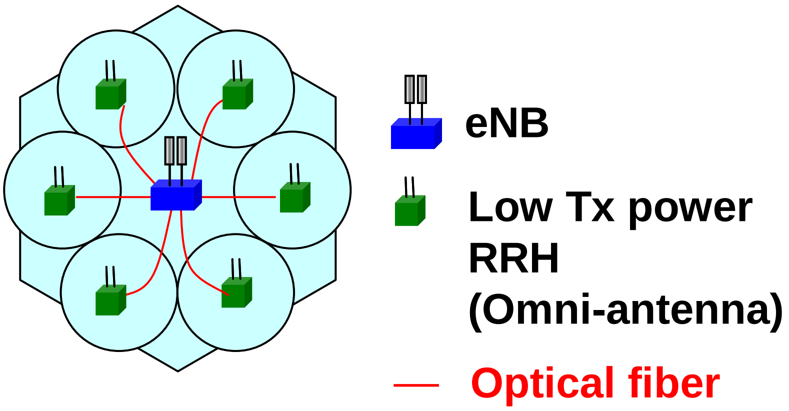


Figure 3-6: CoMP deployment scenario with remote radio heads and fibre backhaul [11]

A further topic was mobility enhancements for Heterogeneous Network (HetNet) deployments [12]. With the main objective to study the impact of small-cell deployments on mobility robustness, e.g. in terms of hand-over failures and small-cell discovery, a simulation methodology has been established, including hand-over failure modelling following the hand-over process on layer 2. Figure 3-7 outlines the modelling approach, which is based on the Time-to-Trigger (TTT) and the subsequent of a hand-over failure event if the channel quality falls below a certain threshold.

Simulation results show a significant increase of both macro-to-pico and pico-to-macro hand-over failures, especially in the case of higher mobility scenarios. The findings of this study item have been partially addressed in a corresponding work item in Rel. 12.

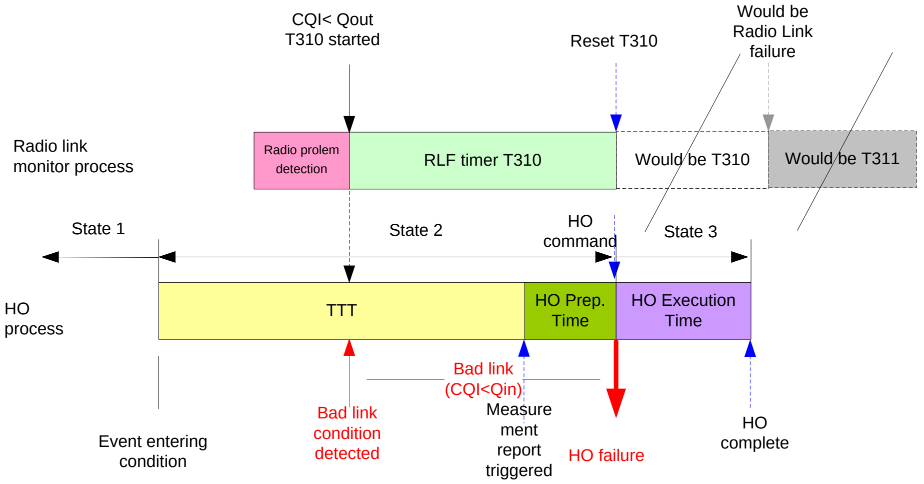


Figure 3-7: Hand-over failure modelling [12]

The impact of different data traffic patterns (e.g. packet sizes, packet inter-arrival times, data volume) has been studied in the WI "LTE RAN Enhancements for Diverse Data Applications" [13]. The main focus was firstly to understand the impact diverse data applications on the existing system, and second to propose enhancement for RRC, Discontinuous Reception (DRX) and resource management in order to facilitate a more efficient data traffic handling.

One of the main findings of this WI was that due to the inability of RAN and UE to differentiate between e.g. background traffic and inter-active traffic, battery power is wasted. This was established by means of simulations based on traffic traces for different traffic types: background, instant messaging, gaming and inter-active content pull. Simulation results for uplink control resources (PUCCH and RACH), for RRC signalling load, for mobility-related signalling and for UE power consumption has been provided.

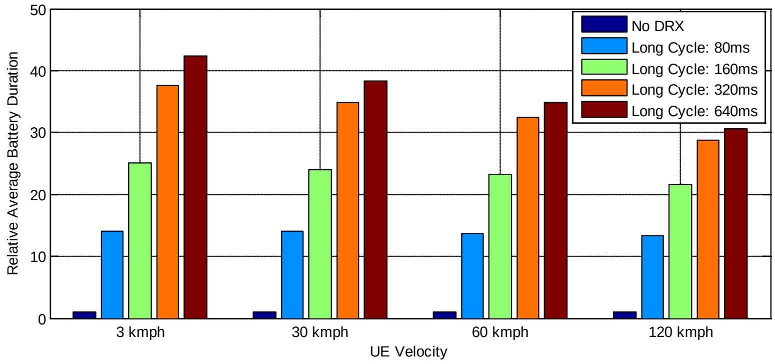


Figure 3-8: Impact of DRX cycles on battery duration [13]

Figure 3-8 illustrates the impact of the DRX cycle length on the average battery duration. Due to this finding, an "assistance information for RRM and UE power optimisations" has been introduced in [9], consisting of a single Power Preference Indication (PPI) bit, which the UE "shall set in accordance with its preference for a configuration that is primarily optimised for power saving (e.g. a long value for the long DRX cycle or RRC connection release) or not."

3.1.3 Release 12

In a workshop of the RAN technical specification group, companies proposed their view of future radio access in LTE Release 12 and beyond [14]. A set of common requirements was identified, including

- Capacity increase to cope with traffic explosion;
- Energy saving;
- Cost efficiency;
- Support for diverse applications and traffic types;
- Higher user experience and data rate;

- Backhaul enhancements.

Small cell enhancements were identified as one of the most promising technologies to fulfil these requirements. Small cell enhancements comprise a set of techniques which aim to increase the capacity and integration of small cells within the current EPS architecture. In the following, several work and/or study items within this context have been approved:

- Carrier based HetNet ICIC for LTE,
- Further enhancements to LTE Time Division Duplex (TDD) for DL-UL interference management and traffic adaptation,
- HetNet mobility enhancements for LTE,
- Machine-type and other mobile data applications communications enhancements,
- Further Downlink Multiple Input Multiple Output (MIMO) Enhancement for LTE Advanced.

Small cell enhancements requirements and scenarios are covered in [15]. This TR contains small cell scenarios considering deployment options, spectrum usage and traffic characteristics, as well as requirements on system, mobility and coverage performance, cost and energy efficiency aspects and security aspects. Figure 3-9 shows a common small cell deployment scenario with two carrier frequencies (F1 and F2), indoor and outdoor small cells, as well as over-lapping and non-over-lapping deployments of small cells with macro cells. For over-lapping scenarios, inter-band CA can be applied, potentially with the macro-cell as PCell.

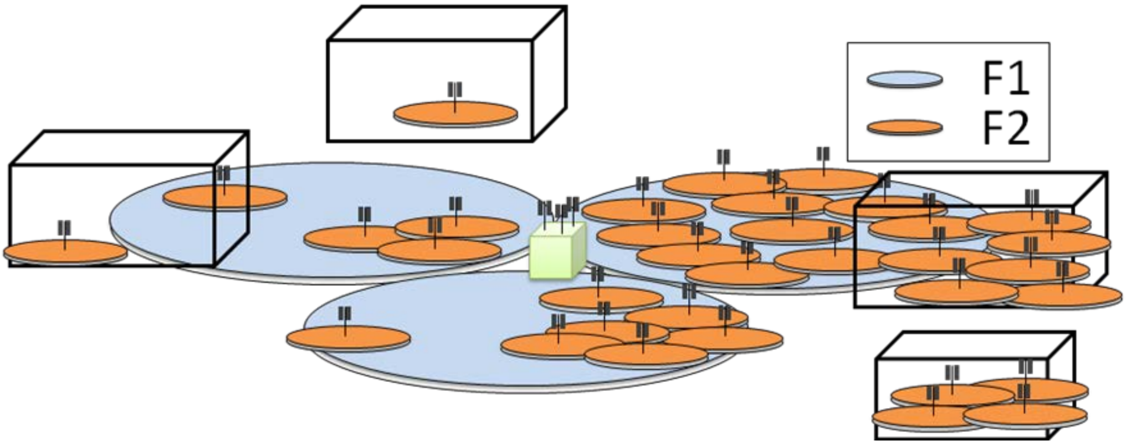


Figure 3-9: Deployment scenarios for small cell enhancements [15]

Wireless backhaul for small cell is categorized into ideal and non-ideal backhaul, according to the employed backhaul technology, and the resulting latency and throughput characteristics. While optical fibre is identified as ideal backhaul with very low latency values, several technologies are categorized as non-ideal as shown in Table 3-1. The priority value indicates the perceived importance of these technologies for the future Release 12 work in 3GPP. According to this categorization, some technologies like Digital Subscriber Line (DSL) access lead to significant backhaul latencies (one-way) of up to 60ms, which may have an impact on the efficiency of RRM schemes.

Table 3-1: Categorization of non-ideal backhaul [15]

Backhaul Technology	Latency (One way)	Throughput	Priority (1 is the highest)
Fiber Access 1	10-30ms	10M-10Gbps	1
Fiber Access 2	5-10ms	100-1000Mbps	2
DSL Access	15-60ms	10-100 Mbps	1
Cable	25-35ms	10-100 Mbps	2
Wireless Backhaul	5-35ms	10Mbps – 100Mbps typical, maybe up to Gbps range	1

3.2 MAC/RRM State of the Art for Mobile Radio Access

The success of mobile cellular networks has resulted in wide proliferation and demand for ubiquitous heterogeneous broadband mobile wireless services. The mobile industry is preparing to meet the requirement of GB traffic volumes and provide uniform broadband wireless service.

Increasing the spatial reuse is known as the most promising approach to improve the system spectral efficiency. According to a recent research, since 1950, the system throughput of cellular networks rose by a factor of 1600 simply by increasing the density of the mobile network [16]. Therefore, operators have complemented the macro networks with local Radio Access Points (RAPs) that further reduce the path losses experienced by mobile users and result high capacity and data rate in areas covered by RAPs. Another advantage related to this solution is the limited impact in terms of capital and operation expenditures associated with low power nodes [17].

However, due to their reduced range (from 10 to 100 meters) a dense deployment of RAPs may be required. Therefore, in such a novel HetNet scenario, a high number of cells of different characteristics may share the same spectrum in a given geographical area, increasing the inter-cell interference. For this reason complex RRM mechanisms are necessary to support the QoS requirements at minimum costs. In particular, RRM aims to improve the system spectral efficiency by increasing user-perceived data rate and limiting overhead. Users, which are either at the cell edge or close to a source of interference, can increase their link robustness through schemes dedicated to the interference mitigation. Finally, by adapting the resource usage to the cell load variations RRM can also introduce great energy saving in cellular networks.

A common approach to classify RRM enablers is to consider the domain in which these schemes operate. RRM techniques, which operate in the space domain, exploit space diversity through, for instance, inter-cell cooperation or MIMO. Other schemes are defined in the time domain and adapt the transmission parameters to the fast variations of the channel/interference instances. Finally, other techniques like CA are implemented in the frequency domain to improve the user performance. Moreover, there are some approaches which simultaneously exploit different domains, i.e., multi-user scheduling that allocates time/frequency resources to several active users.

Following this classification, we present hereafter main RRM schemes, which have been investigated for broadband wireless networks.

- **Carrier Aggregation**

3GPP LTE is able to exploit up to 20 MHz of bandwidth; nevertheless, to satisfy the data rates requirements of future wireless networks (such as those defined by ITU IMT-Advanced), wider bandwidths are necessary (e.g. up to 100 MHz). A single portion of continuous spectrum is often available and hence novel approaches are required.

CA enables to use up to five different component carriers that can have a bandwidth of 1.4, 3, 5, 10, 15 or 20 MHz. The size of the aggregated carriers may differ; however the same number of carriers has to be used in uplink and downlink.

CA results in higher spectral efficiency and system flexibility while maintaining backward compatibility [18]. Other notable advantages come in terms of mobility management, support for operation in HetNets, improved coverage, and interference mitigation [19].

- **Cooperative Transmission**

Cooperative transmission has emerged as promising technique to enhance the performance in current wireless communication technology by exploiting spatial diversity. In contrast with the classic point-to-point communications, in cooperative transmission, several entities cooperate to simultaneously transmit/receive data to/from a mobile user.

The main advantages of these mechanisms are improved coverage, interference mitigation and mobility management [20]. Amongst the different available architecture to operate in a cooperative fashion, we can cite Distributed Antenna System (DAS), relaying, and CoMP. In the following, we give some more details in the last two techniques since they are attracting notable attention from both researchers and industry.

Wireless relays cover smaller areas than macro cells and thus have significantly lower radiated power compared to the eNBs. Basically, they are used to reduce the distance between the user and its serving eNB providing an alternative link, which can be useful when the direct link is in outage. Relays use to operate in a two-stage approach; in the first stage the original message is transmitted from the serving eNB and received at both the relay and the mobile user. In the second stage the relay processes the received message and forwards it to the user (see Figure 3-10). It is straightforward that this scheme can improve the robustness of the direct link as well as improve the coverage in the macrocell area. Furthermore, relaying comes at limited cost of site acquisition and does not required wired backhaul deployment [21].

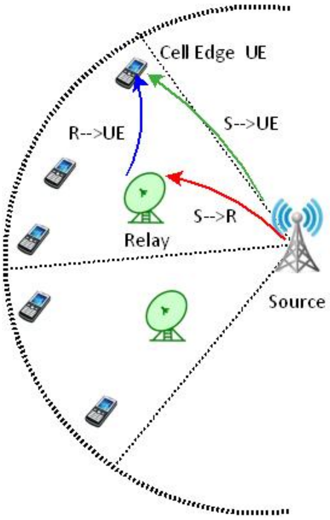


Figure 3-10: Cooperative transmissions through wireless relays.

According to the signal processing stage that is operated at the relays, we can distinguish amplify and forward, decode and forward, and compress and forward relays. In the first case, the relay act as a repeater, which amplifies whatever receives, including noise and interference. In the second approach, the relay tries to decode the received message and forwards the re-encoded message. In compress and forward, the relay quantizes its observation, compresses the quantization index and forwards the compressed information [22]. Unlike decode and forward, which benefits from transmit diversity, compress and forward provides its observation to the destination and thus exploit receive diversity. It is hard to identify an optimal relaying strategy, mainly because the performance of the relay mainly depends on the SINR conditions in which it operates.

The specification of CoMP in 3GPP started in release 11, where 4 scenarios of interest were defined [23]:

- Homogeneous macro network with intra-site CoMP, where cooperation is implemented through eNBs which belong to the same site;
- Homogeneous macro network with inter-site CoMP, where eNBs which belong to different sites coordinate their activity;
- Heterogeneous network with low-power picocells within the macrocell coverage area;
- Heterogeneous network with low-power RRHs, which are located in the same macrocell area.

Furthermore, we can identify three main CoMP schemes:

- Coordinated scheduling/beamforming is an interference management scheme in which user data is available only at serving cell; however, user scheduling and beamforming decisions are implemented through cooperation amongst neighbouring cells.
- On the contrary, in the joint transmission/reception scheme, data is simultaneously processed from multiple sources.
- Finally, in the dynamic point selection scheme, the RAP/eNB serving a given user can be changed, amongst the CoMP elements, at subframe level.

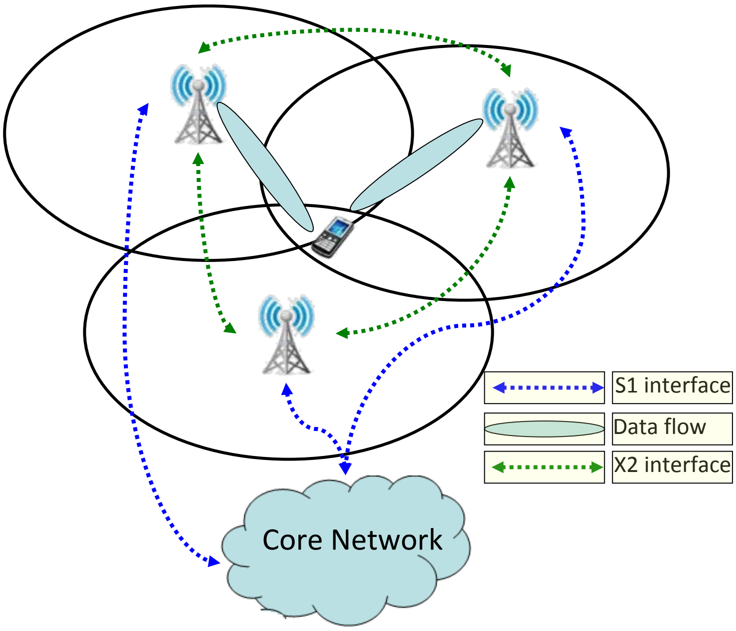


Figure 3-11: Joint transmissions in CoMP

- **Link Adaptation and Multi-User Scheduling**

Multi-user scheduling counteracts the time-varying and frequency-selective nature of the wireless channel and exploits multi-user diversity to maximize the network performance. In this way, a user experiencing a higher SINR will be served with higher bitrates, whereas a cell-edge user, or in general a user experiencing bad channel conditions, will maintain active connections, but at the cost of a lower throughput.

Dynamic Packet Scheduler (PS) performs scheduling decisions every Transmission Time Interval (TTI) by allocating Physical Resource Blocks (PRBs) to the users; it also manages Link Adaptation (LA) by assigning a Modulation and Coding Scheme (MCS) for each transmission [24].

LA exploits the tracking of small-scale fading, which may need frequent channel estimation and channel state information feedback (i.e., Channel Quality Indicator (CQI)), to select MCS for a user depending on the selected set of PRBs. A way to limit the signalling overhead, for instance in full load scenarios, is to implement semi-persistent scheduling [25], which increases the length of the scheduling period but may result in notable loss in terms of user data rate.

Two main adaptive approaches are identified in literature [26]:

- In margin adaptation schemes, QoS is constrained and the objective is limiting the resource usage;
- In rate adaptation, the goal is to maximize the overall capacity while exploiting the available resources.

Another main function associated to the PS is the control of retransmissions.

The destination of data packets has to notify the (un)correct reception by sending a (N)ACK message. When a source receives a NACK, it has to retransmit the same copy of the lost packet. Therefore, according to the HARQ mechanism, the destination tries to decode the packet combining the retransmission with the original version, and will send an ACK message to the eNB upon a successfully decoding.

Basically, the role of the packet scheduler is to decide each TTI between sending a new transmission or a pending retransmission to each scheduled user.

- **3GPP Inter-Cell Interference Coordination**

LTE has introduced ICIC mechanisms mainly to protect cell edge users. These mechanisms operate in the frequency and spatial domain through dynamic management of the available power and bandwidth [27].

LTE normally operate at full frequency reuse, i.e., each eNB uses all the available bandwidth; however, in order to mitigate co-channel interference, it is possible to limit the frequency reuse and protect cell-edge users by allocating different part of the band to neighbouring cells (Hard Frequency Reuse). Nevertheless, in

Hard Frequency Reuse, the spectrum efficiency drops by a factor equal to the reuse factor. More flexible approaches are feasible.

- In Fractional Frequency Reuse, the bandwidth is divided into two parts, which have a different reuse. A first portion is used to serve those users located in the inner part of a cell; however, the second portion is shared amongst interfering cells to orthogonally serve cell edges. This scheme is helpful in uplink transmissions.
- In Soft Frequency Reuse, an eNB transmits in the whole system bandwidth, but using a non-uniform power spectrum. The part of the bandwidth with higher power is likely to be assigned to cell edge users, which experience larger coverage than users located in the inner part of the cell. This approach is beneficial especially for downlink transmissions.

In release 10, 3GPP has introduced enhanced ICIC (eICIC) to limit inter-cell interference in HetNets. eICIC focuses mainly on protecting control signalling from cross-tier interference:

- CA enables macro and low-power RAPs to operate downlink signalling on different CC, while data transmissions can be performed on same CCs.

Furthermore, eICIC exploits also time domain solutions [28]:

- In OFDM symbol shift, the sub-frame boundary of interfering cells is time-shifted to prevent overlap between the control channels.
- In almost blank sub-frames only reference signals, no control or data signals, are transmitted; therefore data transmissions are also protected at costs of reduced spectral efficiency.

- **Interference Mitigation Techniques**

In interference cancellation techniques, the system exploits a-priori knowledge of its interfering user’s message to avoid/cancel interference at the served user. Interference avoidance can be realized at the transmitter through pre-coding techniques that exploits complete knowledge of channel state information such as dirty paper coding [29].

Another well-known interference mitigation technique is Interference Alignment (IA). In IA, users exchange channel state information and jointly design linear precoding matrices, such that the interference signal lies in a reduced dimensional subspace at each receiver [30]. Basically, considering a wireless interference channel with K transmitter–receiver pairs, with IA each user is simultaneously able to send at a data rate equal to half of his interference-free channel capacity to his desired receiver.

Interference mitigation is possible also at advanced receivers through linear and non-liner approaches. In non-linear approaches interfering signal is estimated, decoded and then subtracted from the useful signal, possibly in an iterative manner. On the contrary, in linear approaches, the receiver exploits several antennas to create a null in the direction of the interferer (i.e., interferer rejection receiver).

- **Self-Organizing Networks**

Self-Organizing Networks (SON) refer to an operational paradigm where the wireless network configure and adapt itself to achieve given objectives. The advantage of SON is twofold: first, it enables to reduce manual intervention for repetitive processes. Second, it permits to execute actions that were previously too fast or complex to be handled by a human.

We may identify three main enabler axes in the self-organizing paradigm: self-healing, self-optimization, and self-configuration [31]. Furthermore, there are four different architectures that can be used for implementing various SON use cases [32]:

- NM-Centralised SON: SON solutions where SON algorithms are executed at the Network Management (NM) level;
- EM-Centralised SON: SON solutions where SON algorithms are executed at the Element Management (EM) level;
- Distributed SON: SON solutions where SON algorithms are executed at the Network Element (NE) level;

- Hybrid SON: SON solutions where SON algorithms are executed at two or more of the following levels: NE or EM or NM.

Note that in the case a) and b) decision is taken based on fairly complete system information; on the contrary, in c) global information is not available but cooperation may enable Base Stations (BSs) to achieve a higher level of awareness on the surrounding environment. Although the main objective of the SON concept is to reduce Operational Expenditure (OPEX) in cellular networks [32], self-configuration and self-optimization schemes can be as well implemented to i.e., enable enhanced support for user mobility and interference mitigation.

- **Optimal Resource Allocation**

RRM and MAC protocols can exploit complex optimization algorithms to achieve a global purpose in an adaptive fashion. Both centralized and distributed approaches have been proposed in literature. As well known, distributed solutions limit the overhead and they are more robust since they do not rely on reliability of the central unit; on the contrary, in centralized cases, a single node coordinates control information exchange and radio access. However, the latter architecture can potentially be more efficient in resource usage, by exploiting coordination and global information on network status.

In general, wireless networks exploit advanced optimization algorithms to realize intelligent, fair, and efficient allocation of the available resources, which results in mitigated interference and high data rate. For instance, RAPs may adapt transmission parameters, such as modulation and coding, power transmission, and antenna configuration, with respect to changes of the wireless environment, to efficiently exploit the available resource. Finding the system optimum that takes into account all the constraints of the wireless system requires, however, for practically relevant systems, prohibitively computational cost and a complete knowledge on the network status.

Therefore, in order to reduce complexity, decentralized approaches in which each node acts based on partial knowledge of network status have been proposed. Several approaches have been considered to model distributed network interactions such as graph colouring theory, game theory, stochastic theory, genetic algorithms, and swarm intelligence algorithms.

- Graph theory algorithms [33]: a wireless network can be modelled as a graph G = (V, E) where V and E indicate the vertex vs. the edge sets. Two kinds of representations are available: Node Contention Graph (NCG) and Link Contention Graph (LCG). In NCG, RAPs are represented by nodes while edges indicate that two nodes are in the interfering range of each other (see Figure 3-12). In LCG, the vertex set represents active flows, while edges represent a contention between different flows.

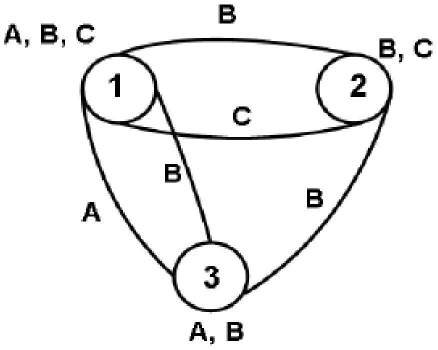


Figure 3-12: A NCG indicating channel availabilities and interference constraints.

- Stochastic algorithms [34]: the evolution of wireless channel can be represented by a stochastic process. In particular, among the various proposed stochastic approaches, Markov chain formulation is the most applied (see Figure 3-13). In these strategies, each node estimates channel usage based on the statistics of local measurements and its historical access experience. Hence, based on the observations, stochastic algorithm is expected to determine a strategy that maximizes the adopted utility function.

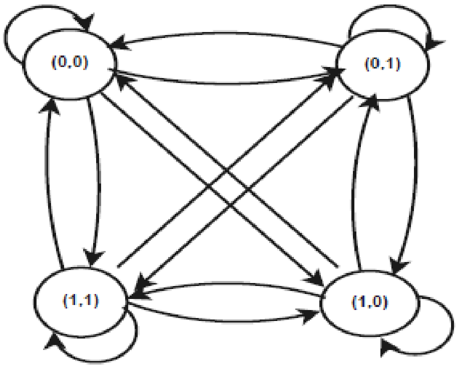


Figure 3-13: The Markov model representing channel state transition {0-idle; 1-occupied}

- Game theoretic algorithms [35]: interaction between competitive base stations can be represented as a game. Game theory efficiently models the dynamics of wireless networks: adaptation and recursive interactive decision process are naturally modelled by a repeated game. Moreover, with game theory each player may adopt a different utility function to pursue specific goals. Interactive behaviours among base stations are represented as a game Γ = <N, {Si}, {ui}>. N is the set of game players, each send/receiver pair is an element of this set; Si represents the strategy space (modulation and coding schemes, transmission power, antenna parameters, etc) of player i; ui is the local utility function that models the scope of player i.
- Genetic algorithms [36]: these are adaptive search algorithms based on the evolutionary ideas of natural selection. An iterative process starts with a randomly generated set of solutions called population. Best individuals are selected through the utility function (called here fitness function). Then, starting from this subset, a second population is produced through genetic operators: crossover and/or mutation. The new population shares many of the characteristics of its parents, and it hopefully represents a better solution. The algorithm typically terminates when it converges to the optimal solution or after a fixed number of iterations. Genetic algorithms are chosen to solve resource allocation problems due to their fast convergence and the possibility of obtaining multiple solutions.
- Swarm intelligence algorithms [37]: Inspired by the collective behaviour of social biological individuals, swarm intelligence algorithms model network users as a population of simple agents interacting with the surrounding environment. Each individual has relatively little intelligence, however, the collaborative behaviour of the population leads to a global intelligence, which permits to solve complex tasks. For instance, in social insect colonies, different activities are often performed by those individuals that are better equipped for the task. This phenomenon is called division of labour. Swarm intelligence algorithms are scalable, fault tolerant and moreover, they adapt to changes in real time.

3.3 MAC State of the Art for Mobile Backhaul Technologies

3.3.1 A brief Recap on Wired Backhaul

Wire-line backhaul relies mostly on two physical mediums: copper and optical fibre. Here we present briefly some key features of these two backhaul wired solutions:

a. Copper-based: Considering the copper-based solutions [38], leased T1/E1 copper lines are extensively used in cellular systems as they can provide suitable support for voice traffic, with deterministic QoS, low latency and jitter [38]. Moreover, T1/E1 lines provide timing and synchronization which is highly required in cellular systems. However, copper lines do not scale easily to provide adequate bandwidth at distances exceeding few hundred meters to support emerging broadband technologies (3G, 4G) [38]. Moreover, another downside of such a technology is that as capacity on the network increases, operators are forced to use multiple leased lines to connect base station sites. That increases the backhaul cost linearly and therefore the cost of backhaul can rise considerably.

b. Fibre-based: Optical fibre can provide a multi-Gbps throughput connectivity that can be achieved using GPON (Gigabit Passive Optical Network) technologies [39]. Optical fibres are usually deployed in urban and sub-urban areas where very high traffic-carrying capacity is more than required. Although a fibre-based backhaul offers long-term support with respect to increasing capacity requirements, this comes at a relatively high Capital Expenditures (CAPEX) and costly deployment.

3.3.2 Wireless Backhaul Technologies

- **Microwave Radios**

Microwave radio can be seen as an alternative choice of backhaul connectivity especially in areas where the wired connection is not available. Microwave transmission operates in both licenced (6 GHz to 38 GHz) and un-licenced (2.4 GHz, 5.8 GHz) spectrum [38].

In general, microwave radio can provide high capacity and availability especially in higher bands. In these bands Line of Sight (LoS) propagation is required, whereas in lower bands (near LoS is possible), which are preferred due to good radio wave propagation, we may have less available bandwidth and long range interference [38]. Microwave radios also require high gain directional antennas to establish long range fixed links due to their short wavelengths. This results into narrow beam widths and for that purpose alignment is required on installation.

Figure 3-14 illustrates an example deployment of 3 BSs connected through microwave radio, where either LoS or near LoS propagation is available.

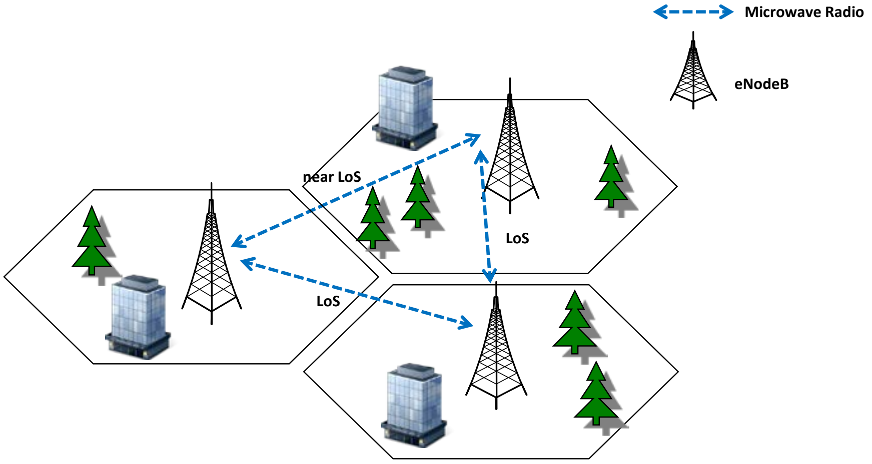


Figure 3-14: LoS and near-LoS microwave backhaul

- **Wi-Fi**

Wi-Fi (IEEE 802.11) [40] was initially designed for indoor connectivity and operates in 2.4 GHz and 5 GHz un-licenced bands. Further research advances in 802.11n [40], in terms of range and capacity enhancement, transformed Wi-Fi to a potential low-cost backhaul solution which can replace microwave links. In particular, the latest Wi-Fi technology has been developed to combine integrated adaptive directional antennas with smart meshing technology and predictive channel management [38]. By using smart mesh techniques together with the employment of adaptive antenna arrays for point-to-point connectivity, the complexity of the alignment and the installation process can be decreased. The combination of these technologies can make the use of Wi-Fi feasible for both line-of-sight and non-line of sight backhaul applications.

- **Free-Space Optical Backhaul**

Free-Space Optical (FSO) backhaul is a LoS technology that uses invisible beams of light to provide optical bandwidth connections [41]. FSO is a well-known technology from early military operations where beaming lasers were used for ship-to-ship communication [42]. The main drawback in this technology used to be its limiting range and its dependency on the changing weather condition. However, further advances in laser technology [42] enable FSO to provide simple, point-to-point high bandwidth communication. An example of point-to-point FSO is shown in Figure 3-15.

An FSO system can provide high bandwidth (155 Mbps- 1.2 Gbps) by enabling optical technology which involves the transmission of voice, data and video though the air using lasers [41]. The main advantage of FSO is its low costs of deployment and maintenance and its availability in un-licenced spectrum. Moreover, FSO uses the same optical transmission wavelengths as fibre optics (850 nm, 1550 nm); hence the fundamental similarities to fibre optic (except using air as the medium of transmission instead of fibre), makes FSO a strong candidate to support future packet-centric networks. On the other hand, the main drawback of FSO is the requirement of high-stability mounting and the dependency on obstructions and fog attenuation. For terrestrial links, the maximum range of FSO systems is around 2km.

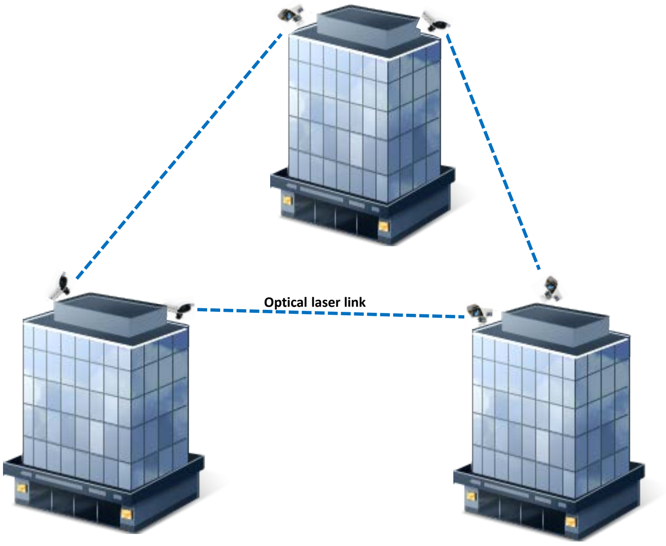


Figure 3-15: Point-to-Point FSO backhaul

- **Satellite Backhaul**

Satellites are the only viable platform to overcome distance and geographic barriers so as to deliver service in the rural area. Regarding the backhaul, satellite communication can offer solutions for very remote locations where no other technologies can be implemented [38]. An example deployment is presented in Figure 3-16.

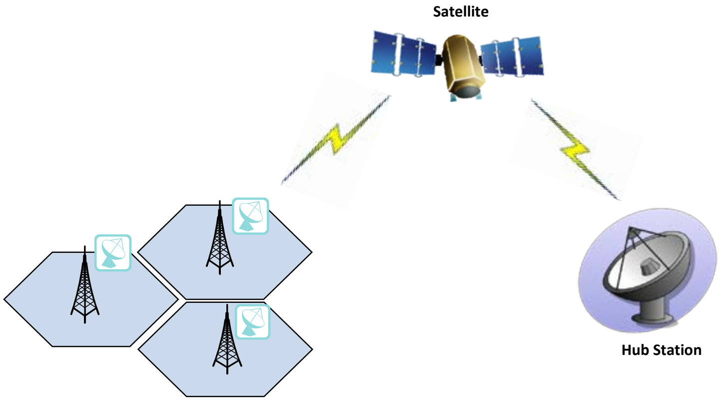


Figure 3-16: Satellite backhaul example

The advantages of satellite backhaul are their short installation times and flexible coverage. Furthermore, satellite communication can also deliver low installation cost due to its efficiency and flexibility as a one-to-many medium [38]. On the other hand, the main drawbacks are the cost of satellite communications which is high, especially for high data rate transmission, and the long round trip transmission delay over the geostationary satellite.

- **mm Wave**

Millimeter Wave (mmW) radio applies in concept to any RF technology operation in the 30-300 GHz range, but is generally used to discuss 60-80 GHz, also known as “E-band” [43]. In this context, several GHz-wide bandwidths are available and able to provide high capacity even with low-order modulation schemes.

In addition to the high-data rates, propagation in the ≥60 GHz band has unique characteristics that add other benefits, such as excellent immunity to interference, high security, reuse of frequency, and almost world-wide availability of unlicensed spectrum [43].

Here to mention that mmW radio requires clear LoS propagation and its range is restricted by the oxygen absorption which attenuates (weakens) ≥ 60 GHz signals over distances, so that signals cannot travel far beyond their intended recipient. Therefore, high gain directional antennas are used in order to compensate for the large free space propagation losses.

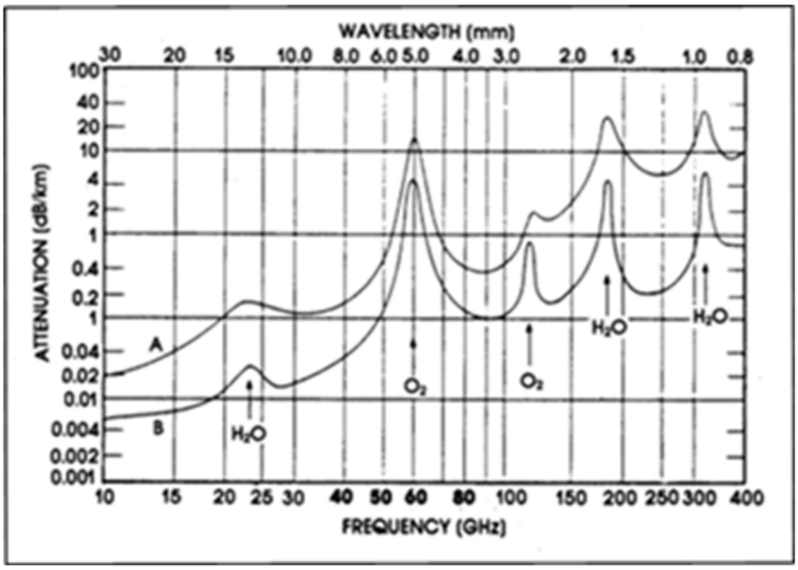


Figure 3-17: Impact of oxygen absorption and rainfalls to signal attenuation in mmW radio

3.3.3 Wireless Backhaul Topologies

- **Point-to-Point:** A mode of operation whereby a link exists between two network entities. Individual point to point links between nodes (i.e. access points and / or gateways) can be connected to form chain, tree or ring [39] topologies. In chain and tree topologies traffic is aggregated towards the Point-of-Presence (PoP) and the link capacity can be increased based on the downstream cells. In ring topologies, additional redundant links are included to improve resilience to link outages.
- **Point-to-Multi-point**: A mode of operation which allows a network entity to transmit/receive data to multiple entities. In cellular systems, a hub transceiver forms multiple links to a number of access points [39]. The total hub capacity is shared among the underlying access points, hence statistical multiplexing gains can be realised.
- **Mesh**: A wireless mesh network is a peer-to-peer, multi-hop wireless network in which participant nodes or access points cooperate to route packets [44]. In this framework, nodes in the network form multiple redundant links to improve resiliency and routing algorithms can be used to find the least cost path taking into account network loading and link outage.

3.3.4 Important MAC/RRM Challenges

In wireless mesh backhaul networks the current MAC protocols are not able to utilize the entire bandwidth provided by the physical layer, as the MAC protocol is sub-optimal for multi-hop networks (initially designed for single-hop networks) [44]. The sub-optimal performance of MAC layer poses some key challenges that should be addressed in emerging wireless backhaul networks:

- **Intelligent Channel Assignment:**

One of the key issues in multi-hop backhaul networks is the interference that can be caused by nodes that are transmitting/receiving data at the same spectrum. This usually leads to the hidden and exposed terminal problem [44] which can cause resource starvation of some nodes in the system. For that reason, fixed channel assignment is seen as a feasible remedy to this problem assuming a non-overlapping multi-radio multi-channel network [44].

However, in a high node density scenario the number of radios to be used by each node might not be sufficient. Therefore, the design and employment of efficient and intelligent challenge assignment is required to provide spectral efficiency among multiple radios.

- **Resource Utilization:**

A challenge that can affect the system's performance is the utilization of the resources by each node. The communication through multiple radios with multi-channel capabilities might cause inter-operability issues for a variety of MAC, routing protocols [44]. Hence, the scheduling of flows, assuming multiple radios transmitting on non-interfering channels, should be done intelligently to maximize the resource utilization.

- **Support for QoS:**

Another important challenge is the QoS provisioning in a multi-radio multi-channel backhaul network [44]. The nodes in the wireless mesh backhaul are going to support different applications (video, voice) with different QoS requirements. Therefore the provisioning of QoS considering different applications is a major challenge that should be further investigated.

- **Routing, Load Balancing:**

In multi-hop backhaul, the way packets are routed across the network should be further investigated to ensure that the path selection does not only consider links of high bandwidth, but also takes into account link stability to avoid frequent route fluctuations and channel diversity to minimize interference. Moreover, routing algorithms should be investigated to ensure that the load at the nodes at the backhaul is balanced to prevent some access points to become bottleneck nodes.

- **T-Put vs. Coverage Trade-off:**

One of the main objectives in a multi-hop wireless backhaul network is the system's capacity which can be seen as the total throughput traversing a given set of nodes [45]. However the requirement for high data rate across the system can be restricted by the BS range limitations imposed by transmission power. This can trigger the deployment of a dense BS environment with low cost (wireless) backhaul connectivity [45].

Therefore, the trade-off of the network capacity versus the transmission range should be investigated in terms of routing and scheduling to address the network dimensioning issue [45].

3.3.5 Solution frameworks

The aforementioned challenges in wireless mesh backhaul networks necessitate the employment of intelligent mechanisms to achieve efficient channel utilization, load balancing and network capacity.

- **Channel Assignment:**

In multi-radio Wireless Mesh Networks (WMN), the channel assignment problem is considered as NP-hard combinatorial optimization problem [46]. Therefore, three categories of heuristic channel assignment schemes can be defined to efficiently solve this problem, namely Fixed, Dynamic and Hybrid schemes.

As discussed above, in fixed assignment [46] the channel assignment remains constant (or changes in larger time scale), providing ease of coordination between different radio nodes. These schemes can be further divided into Common Channel Assignment (CCA) and Varying Channel Assignment (VCA). In CCA all the radios in the system are assigned the same sub-channels, whereas in VCA nodes are partitioned into groups and can be assigned different sets of channels.

On the other hand, dynamic channel assignment [46] enables the radio nodes to switch the channels dynamically based on the traffic load. Both sending and receiving radio have to operate at the same channel in a particular moment. However, assuming we have multi-hop communications, an agreement between nodes is required to ensure that they operate at the same channel before their coordination. Here, some interesting distributed solutions have been proposed in literature to improve network capacity and provide load balancing [47].

An alternative category that combines both fixed and dynamic channel assignment mechanisms is the hybrid class of schemes. In this case, radios can be partitioned in two sets one for fixed and one for dynamic assignment [46]. Therefore a set of fixed radios can use a dedicated channel (CCA or VCA) and the rest set of radio nodes can change dynamically the channel they utilize based on the channel interference and the load factor.

- **Routing and Scheduling:**

Considering the discussed challenges for the wireless mesh backhaul network design, routing and scheduling can be seen as two key operations that can provide high resource utilization, network capacity and load balancing in dense small cell networks. In the state-of-the art literature on WMN, routing and scheduling can be implemented either jointly or separately and can be further categorized as follows:

- Joint Routing and Scheduling [48]: In this category, routing and scheduling can be seen as a joint optimization problem which is performed at a central entity. In particular, the decisions of which sequence the packets are going to be transmitted (scheduling) and the selection of the path they follow (routing) are made jointly in a central entity, taking into account the traffic load and the resource utilization.
- Distributed Routing and Centralized Scheduling [48]: In this case, routing is decided in each node in de-centralized way though signalling exchange, and the scheduling is performed in a central entity.
- Distributed Routing and Scheduling [48]: Here, the path selection to the next node is decided at each node and thereafter scheduling is performed in a decentralized way either coordinated or not).
- Hybrid Routing and Scheduling [48]: This category includes both distributed and centralized routing and scheduling for different groups of nodes.

3.4 State of the Art for Cloud RAN

In the recent past, the “cloudification” of the RAN was proposed by different vendors and operators [1][49][1][50][1][51]. This approach advocates the shift of the baseband processing away from the physical location of the RAP into a “base station pool”, e.g., located in a data centre. This philosophy is adopted from cloud computing, where resources are allocated on demand. In this Cloud RAN (C-RAN) application, this allows for a shift of processing power from the base stations into the base station pool, where it can be employed more efficiently: Instead of base stations being provisioned based on their maximum load, with the cloud RAN approach, thin provisioning based on the maximum overall sum load of the whole network is possible. Furthermore, the processing power in the base station pool can be adapted to the instantaneous load.

This concept has the significant drawback that high-capacity links between the RRH, being the interfacing element to the air interface, and the base station pool are required since the raw receive / transmit signals have to be conveyed on these links. For that purpose, all existing C-RAN architectures rely on fibre for this purpose. They are detailed in the following.

3.4.1 Existing Cloud RAN Architectures

- Alcatel Lucent [1][52]: ALU offers a commercial product called “LightRadio” that allows for detachment of the RF front ends from the baseband processors using CPRI (Common Public Radio Interface) fibre links. The selling point of this product is the possibility to cluster the baseband processing of base stations in a certain area in order to save space and, correspondingly, rent. The baseband processing units, however, are still proprietary and, furthermore, an elastic scaling of processing power based on current load demands is not possible.

  Nevertheless, ALU researchers presented recently a different concept going into that direction. In [1][53], a testsuite was presented for baseband processing on general purpose servers using the Eurecom OpenAir baseband processing stack combined with the CloudIQ management framework that addresses the shortcomings of the current LightRadio architecture. At the moment, baseband processing is performed entirely in software, but the use of hardware acceleration (e.g., for the FFT) is intended.

- China Mobile [1][54]: Operator China Mobile proposes its own C-RAN architecture. This architecture relies on dedicated "dark" fibres (installed but unused fibre) for the interconnection of baseband processing servers and the remote radio heads. The complete software solution running on general purpose servers supposedly supports GSM, CDMA and LTE. For short ranges between RRH and baseband processor (in particular indoor applications), China Mobile suggests the use of a Passive Optical Network (PON) in order to save costs but still exploit the benefits of centralization.
- ZTE [1][55]: Chinese vendor ZTE claims to have demonstrated a working C-RAN installation providing 2G (GSM) service, using dedicated fibre links.
- Huawei [1][56]: Huawei has also developed a C-RAN architecture that is currently in a pre-commercial state. This system uses CPRI links between RRH and the baseband processor. Huawei is collaborating with Intel as an expert in server technology.
- Nokia Siemens Networks [1][57]: As a commercial product, NSN offers the "LightNet" architecture, of which "LightRadio" is a part. Similar to ALU's solution, this product allows for detachment of a RRH from a baseband processing unit. This requires a dedicated fibre link, either a dark fibre or multiplexed using Coarse Wavelength Division Multiplexing (CWDM).
- IBM [1][58][1][59]: IBM has presented a cloudified WiMax implementation using a completely software-defined baseband processing. This architecture proposes the use of standard 1 GbE / 10 GbE Ethernet links for the connection of the remote radio heads.

3.4.2 Existing Protocols/APIs

A significant number of existing architectures use the CPRI interface [1][60], which has been standardized precisely for that application. CPRI defines a Layer 2 protocol, intended for point-to-point connections, which hinders the switching of CPRI links. The same is true for the OBSAI (Open Base Station Architecture Initiative) RP3-01 interface [1][61], which is a mere extension of the OBSAI set of specs that define interfaces within a base station. To our knowledge, this protocol is not used by current cloud RAN architectures.

IBM proposed the use of standard 1 GbE / 10 GbE Ethernet for connection of RRHs to the baseband pool. This approach has the advantage that existing infrastructure, in particular Ethernet (Layer 2) switches, can be reused.

CPRI links in general require a "dark" fibre or at least a dedicated wavelength in a CWDM. This hinders the joint use with existing fibre optic links.

The Small Cell Forum proposes an API (Application Platform Interface) for interaction of the L2/L3 functions with the L1 for use in LTE conforming (Home) eNBs. It defines two interfaces, P5 and P7, of which the former is intended for PHY configuration, while P7 is an interface of the data plane and interfaces with the MAC layer. These two protocols were originally defined by the Femto Forum in their Femto Application Platform Interface (FAPI).

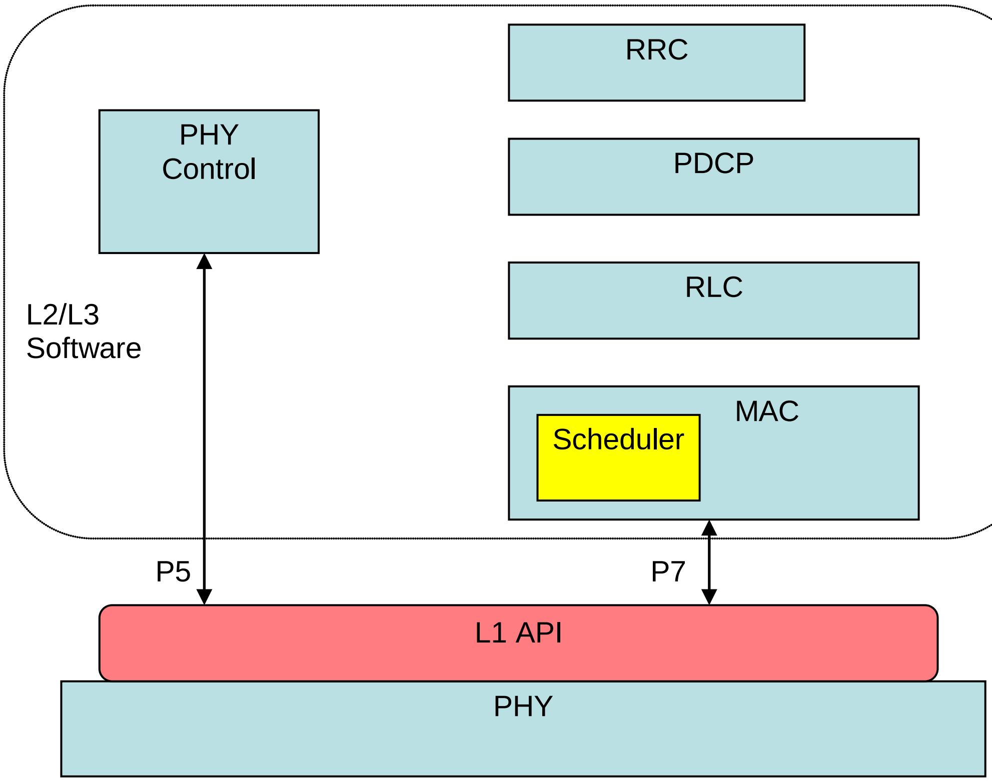


Figure 3-18: Interactions with the eNB L1 API as defined by the Small Cell Forum

3.4.3 Functional Split

For the existing RAN implementations using cloud technology, the main motivation comes from the traditional cloud computing point of view and hence the shift of processing is carried out at very lower level. Furthermore the functional split for eNB cloud processing is not dynamic but fixed. This split is currently carried out either at L0 or L1.

In current implementations, the detached RRH solely plays the role of the converting element from the analogue to the digital domain, i.e., no baseband processing takes places there, the raw receive and transmit signals are forwarded through the e.g., CPRI, link to the baseband processing pool where either a general purpose server or a proprietary system will perform the actual baseband processing. So the functional split is located between L1 and L0.

When Home eNBs are employed, the eNB L1 API allows for a separation of L1 processing and the higher layers. L1 functions are performed “on-site”, while L2/L3 can physically be shifted away to a centralised entity. Therefore, the functional split is in this case located between L2 and L1.

Alcatel-Lucent proposal in [50] uses RRH and only BB IQ to RF signal conversion is carried out at remote radio heads. In other study of Alcatel-Lucent focusing on CloudIQ [49], the split between remote units and baseband pool is proposed on L0, hence IQ baseband signals are conveyed to the cloud pool of resources over the fibre. They discuss the possibility of information exchange between different base band units at various functional levels (e.g. before or after FFT/IFFT operation) but the functional split from the remote radio heads to base band units stays fixed.

NSN liquid radio [55] proposes simple RF units which are communicating to baseband pool through fibre. They define many different functionalities of their proposed liquid radio but the proposed ideas go very close to the software radio proposals where multi-standard multi-function capabilities are provided.

3.5 State of the Art for Cloud Platforms

3.5.1 Definitions of Cloud Computing

Internal Report IR5.1 contains in Section 3.3 the definitions of cloud computing and several key terms that describe the cloud specific types and features. Instead of duplicating that content in this document, please refer to that section as an intro for the next section, where we drill down in the selection of a suitable cloud “flavor” for the RAN case.

3.5.2 Cloud Infrastructure for iJOIN

A current research trend in mobile telcos is to deploy OSS (Operational Support Systems) and some EPC Core Network components in Infrastructure as a Service (IaaS) private clouds [1][62], with industry standard hardware platforms. This standardizing of the infrastructure enables (only for selected components) the introduction of virtualization (virtual machines), the usage of standard operating systems and middleware enterprise software, and therefore achieving a better flexibility in the data centre resource usage and lowering IT costs. The choice for private cloud is motivated by better control on deployment, security and privacy management.

The challenge for iJOIN is to further extend the cloud boundary to selected E-UTRAN functionality. The requirements of iJOIN in terms of guaranteed performance, network throughput and QoS can be managed only in a **private cloud**, where resource allocation is more deterministically controlled, users are limited in number and capabilities, and peaks of load can be managed in a more predictable way. This is in partial contradiction with the attribute “Shared” associated typically with public cloud [1][62], but can still be considered a valid case for a strictly controlled private deployment model.

Still, the variant of “virtual private cloud” can be an option, where an external provider offers a set of dedicated resources connected through a secure channel. This option needs to be validated from the network latency perspective on the network path between the telco data centre, the external provider and the eNBs.

The software that iJOIN plans to run in the cloud is not generally available “off-the-shelf” as in the typical public cloud provider service catalog; in addition the deployment and operation of this software needs to be under strict control of the telco/service provider operators.

Therefore, the envisioned service model is IaaS, because this is the only way to build a system with guarantees on execution performance for the very specific kind of software iJOIN is dealing with. Platform as a Service (PaaS) [1][62] would provide a too high level generic programming environment, while the final solution that iJOIN can envision might potentially become a candidate for a future Software as a Service (SaaS) [1][62] model (once it has been refined, optimized and standardized) where the service might be offered by an service providers external to the telco.

4 iJOIN MAC/RRM Candidate Technologies

In this section we define the MAC/RRM technologies for the radio access network and the backhaul network that are promising candidates to meet the challenges of dense deployment of small cells. These CTs enable a holistic design of radio access network and backhaul network.

Table 4-1: List of iJOIN MAC/RRM CTs

CT	Topic
3.1	Backhaul link scheduling and QoS-aware flow forwarding
3.2	Partly decentralized mechanisms for joint RAN and backhaul optimization in dense small cell deployments
3.3	Energy-efficient MAC/RRM at access and backhaul
3.4	Computation complexity and semi-deterministic scheduling
3.5	Cooperative RRM for inter-cell interference coordination in RANaaS
3.6	Assess and increase utilization and energy efficiency
3.7	Radio resource management for scalable multi-point turbo detection/In-network Processing
3.8	In-network-processing for RX cooperation
3.9	Rate adaptive strategies for optimized uplink transmissions

The following table lists which CT will be applied to which of the iJOIN Common Scenarios (CS) defined in IR5.1. As a partner may change his interest with respect to the use cases to be investigated, the given assignment is just preliminary and up to further changes.

Table 4-2: Mapping of MAC/RRM CTs to iJOIN CSs

Scenario	CT 3.1	CT 3.2	CT 3.3	CT 3.4	CT 3.5	CT 3.6	CT 3.7	CT 3.8	CT 3.9
1. Stadium	x	o	o		o				
2. Square	x	x	x	x	x	x		x	x
3. Wide-area continuous coverage				x		x			
4. Indoor (Airport / Shopping Mall)	o	o	o		o		x	x	x

Here, “x” means that the CS will be considered, whereas “o” denotes that the CS may be considered.

4.1 CT 3.1: Backhaul Link Scheduling and QoS-aware Flow Forwarding

4.1.1 Scenario Description

This scenario considers a very dense small cell network deployment which can be connected to core network through optionally deployed Central Units (CUs) in order to enable higher coordination with limited overhead and delay.

In this work, our main focus will be on RRM strategies based on global /network-wide objective functions according to lessons learned from convex optimisation theory. In particular, link scheduling and packet forwarding would be coupled with MAC and Interference management in this scenario.

In this technical scenario, assuming wireless backhaul (microwave / mmW) between iSCs, we narrow down our focus on two other challenging problems:

- Firstly, to identify links to be scheduled per time slot taking into account the target global objective for the network (in terms of maximizing backhaul capacity or aggregate utility).
- Secondly, to identify flow(s) to be scheduled per link in a mesh network (targeting minimum QoS requirements besides the global objective).

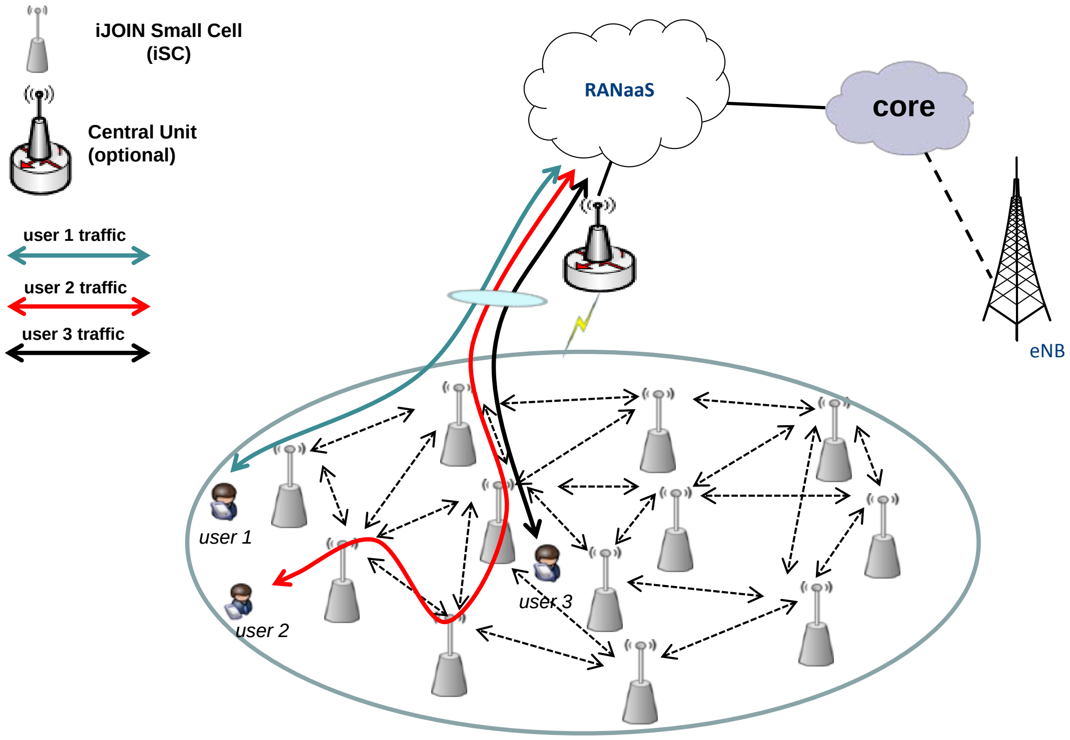


Figure 4-1: Backhaul link scheduling and QoS-aware flow forwarding

4.1.2 Assumptions

iJOIN Small Cells (iSC) can be connected through an area-based iJOIN Network Controller (iNC). This unit aims to manage a multitude of iSCs in a dense area and connect the iSCs to the core network / RANaaS platform through the iJOIN Transport Node (iTN).

X2 / J2 interface can be used for signalling exchange in a cluster of small cells as well as the small cells and the central unit.

Table 4-3: Assumptions of CT 3.1: Joint path selection and radio resource scheduling

Assumption	Description
A.1.1	Area-based iNCs to cover a multitude of dense small cells for coordination purposes
A.1.2	X2 / J2 link amongst neighbouring small cells and small cell-central unit
A.1.3	Finite backhaul capacity
A.1.4	Large number of iSCs in a local area

4.1.3 Technology Requirements

Synchronization amongst iSCs is required to manage the backhaul channel assignment and link scheduling in a centralized way while satisfying QoS requirements.

Table 4-4: Requirements of CT 3.1: Joint path selection and radio resource scheduling

Technology requirements	Description
R.1.1	Synchronization between iSCs

4.1.4 Mapping to iJOIN Architecture and Objectives

The main objective is the investigation of novel concepts for a joint design of MAC and scheduling for access and backhaul in very dense small cell deployments taking into account the backhaul availability and QoS traffic differentiation.

Considering the processing capability in RANaaS, the backhaul radio resource allocation and link scheduling can be managed centrally (or semi-centrally) in dynamic manner. By this, the backhaul channel utilization can be optimized, while satisfying the users' QoS requirements for different types of traffic.

4.2 CT 3.2: Partly decentralized mechanisms for joint RAN and backhaul optimization in dense small cell deployments

4.2.1 Scenario Description

Cell selection mechanism associates mobile terminal(s) to neighbouring RAP(s), which are able to satisfy service request. This process is activated when a user access to a wireless network (i.e., cell selection), or when a mobile leaves the idle mode (named as cell reselection). Generally, the mobile device measures the SINR related to several RAPs and maintains a list of the BSs (called the active set) associated with best detected signal, accordingly [63].

Hence, during the cell (re)selection process, the mobile sends a subscription request to RAPs according to the order indicated in the active set. This scheme is efficient in homogenous wireless network scenarios, where all the eNBs have the same irradiated power, backhaul, average cell load, etc; nevertheless, it may result in limited performance in HetNets, where different type of RAPs are located in the same geographical area [64].

The imbalance in the radiated power between eNB and small cell RAP does not permit mobile terminals to connect to the closest RAP, which constrains uplink data rate and reduces the mobile battery life.

3GPP introduced *range expansion* mechanism to increase macrocell offloading by expanding the actual coverage area of small cells [65]. However, novel cell selection schemes, which also consider the cell backhaul capacity, are required [66].

Here we consider a dense deployment of picocells with heterogeneous traffic requirement and backhaul capacity. We aim to investigate relationships between RAN capacity, cell load, resource scheduling (both at the backhaul and at the radio access), and backhaul capacity. Moreover, we aim to propose innovative cell selection mechanisms, where the above parameters are jointly considered.

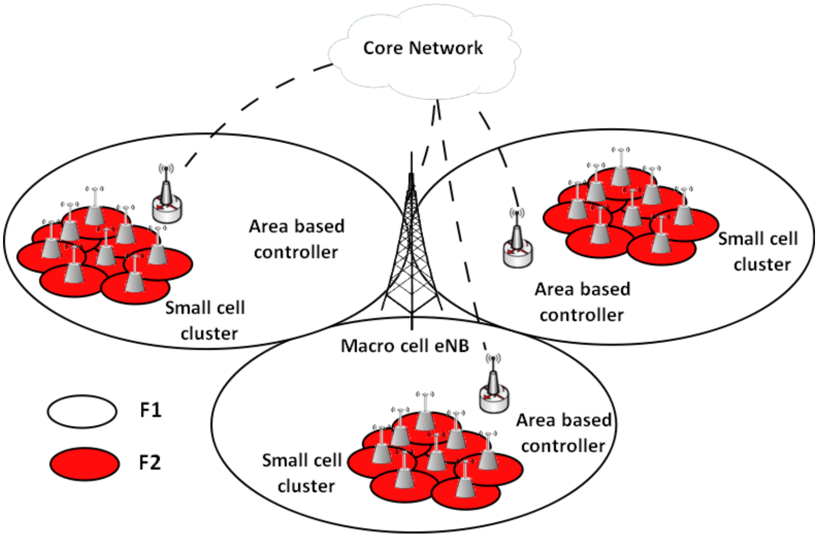


Figure 4-2: Cluster of small cells under the coverage of a macrocell

4.2.2 Assumptions

iSCs are assumed to be associated to a local orchestrator (i.e., the iNC node), which manages a cluster of small cells and connect the small cells to the core network/RANaaS platform.

J2 interface is assumed to enable direct exchange of information amongst neighbouring iSCs, between a cluster of iSCs and its iNC, and amongst neighbouring iNCs; furthermore, it may be used to permit coordination amongst iNCs and eNBs located in the same area. Its content will be investigated.

J1 interface presence is assumed between iNCs and the RANaaS platform. “Logical” J1 interface goes through the “physical” small cell backhaul. Its content will be investigated.

Table 4-5: Assumptions of CT 3.2: Partly decentralized mechanisms for joint RAN and backhaul optimization in dense small cell deployments

Assumption	Description
A.2.1	X2 link amongst iNCs
A.2.2	X2 link amongst iNCs and eNBs (optional)
A.2.3	J1 link amongst iNCs and RANaaS
A.2.2	Limited backhaul capacity
A.2.3	Backhaul links may be independent and have different characteristics
A.2.4	Required data rate may be higher than the available cell capacity due i.e., to cell load and backhaul capacity

4.2.3 Technology Requirements

Synchronization amongst small cells is required to manage the cell (re)selection in a centralized way while satisfying QoS requirements.

Table 4-6: Requirements of CT 3.2: Partly decentralized mechanisms for joint RAN and backhaul optimization in dense small cell deployments

Technology requirement	Description
R.2.1	Synchronization amongst iSCs

4.2.4 Mapping to iJOIN Architecture and Objectives

By introducing novel cell selection mechanisms, which jointly consider resource allocation at RAN and backhaul, cell load, and backhaul capacity, we aim to improve the overall system throughput. Furthermore, such strategies will enable to better exploit the available resource leading in higher utilisation efficiency.

4.3 CT 3.3: Energy-Efficient MAC/RRM at Access and Backhaul

4.3.1 Scenario Description

We consider a dense deployment of local RAPs, which are interconnected through a backhaul, which is characterized by limited capacity and finite latency.

Dense deployment of small cells may result in increasing the overall energy consumption in cellular networks. Energy efficiency can be improved by exploiting the fundamental trade-offs of green communications, which limit the mismatch between the network available resources and the service request [67].

iJOIN will develop adaptive and cooperative strategies amongst neighbouring small cells, which may efficiently use their resources to maximize the area energy efficiency while taking into account backhaul limitation.

In particular, cell Discontinuous Transmission (DTX) [68], which enables BSs to switch off radio in sub-frames where there are no user data transmissions, and new carrier type [69], which is a 3GPP release 12 solution to reduce signalling at small cells, can be combined to limit energy consumption at RAPs.

To assess our studies, we will evaluate the area energy efficiency, measured in a bits/Jule/unit-area, required to satisfy QoS constraints within pre-defined backhaul limits.

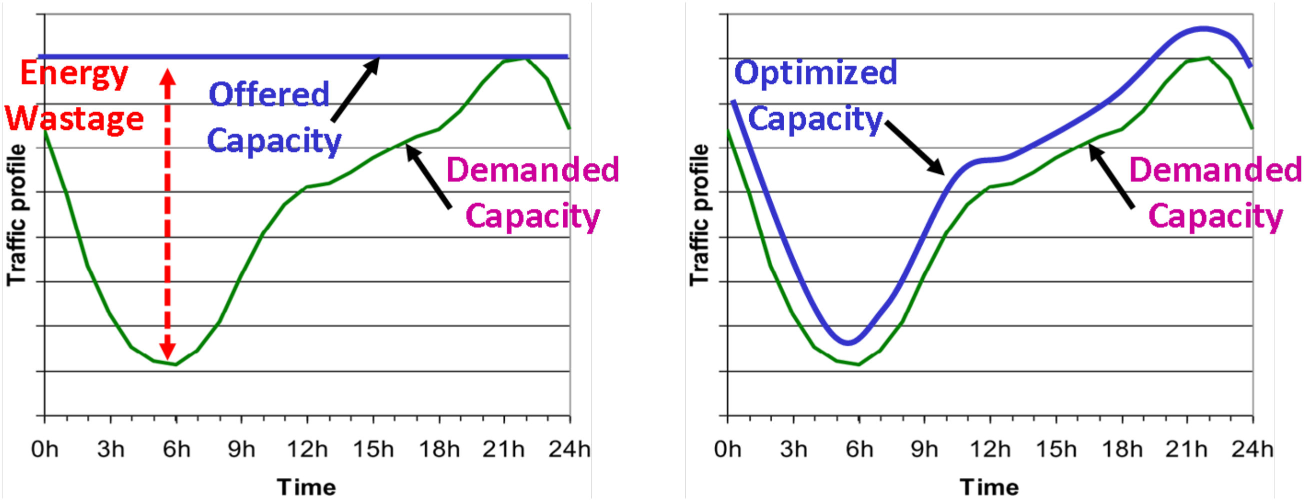


Figure 4-3: Adaptation of the offered capacity to demand to increase power efficiency

4.3.2 Assumptions

iSCs are assumed to be associated to a local orchestrator (i.e., the iNC node), which manages a cluster of small cells and connect the small cells to the core network/RANaaS platform.

J2 interface is assumed to enable exchange of information in a cluster of small cells as well as the small cells and their local controller. Its content will be investigated.

Table 4-7: Assumptions of CT 3.3: Energy-efficient MAC/RRM at access and backhaul

Assumption	Description
A.3.1	J2 link between iSCs and the iNC
A.3.2	X2/J2 link amongst neighbouring iSCs
A.3.3	Large number of iSCs in a local area
A.3.4	Finite backhaul capacity
A.3.5	FDD based small cells for channel feedbacks and data transmission

4.3.3 Technology Requirements

Following requirements are considered, based on the assumptions and current state of the art:

- Low probability of backhaul overflow due to largely accumulated radio access rates
- Synchronization between iSCs

According the assumptions and the state of the art, the only technology requirements are the synchronization between ISCs and a low probability of overflow in the backhaul because of too high radio access rates.

Table 4-8: Requirements of CT 3.3: Energy-efficient MAC/RRM at access and backhaul

Technology requirements	Description
R.3.1	Low probability of backhaul overflow due to largely accumulated radio access rates
R.3.2	Synchronization between small cells

4.3.4 Mapping to iJOIN Architecture and Objectives

By introducing novel energy efficiency enablers, iJOIN will increase the utilisation efficiency of available resources in cellular networks. Such an approach will enable to reduce the energy-per-bit of current systems, which in turn limit the cost of operating small-cell networks. Furthermore, iJOIN will increase the utilisation efficiency in order to more efficiently exploit existing resources and to support the improved energy- and cost-efficiency.

4.4 CT 3.4: Computational Complexity and Semi-Deterministic Scheduling

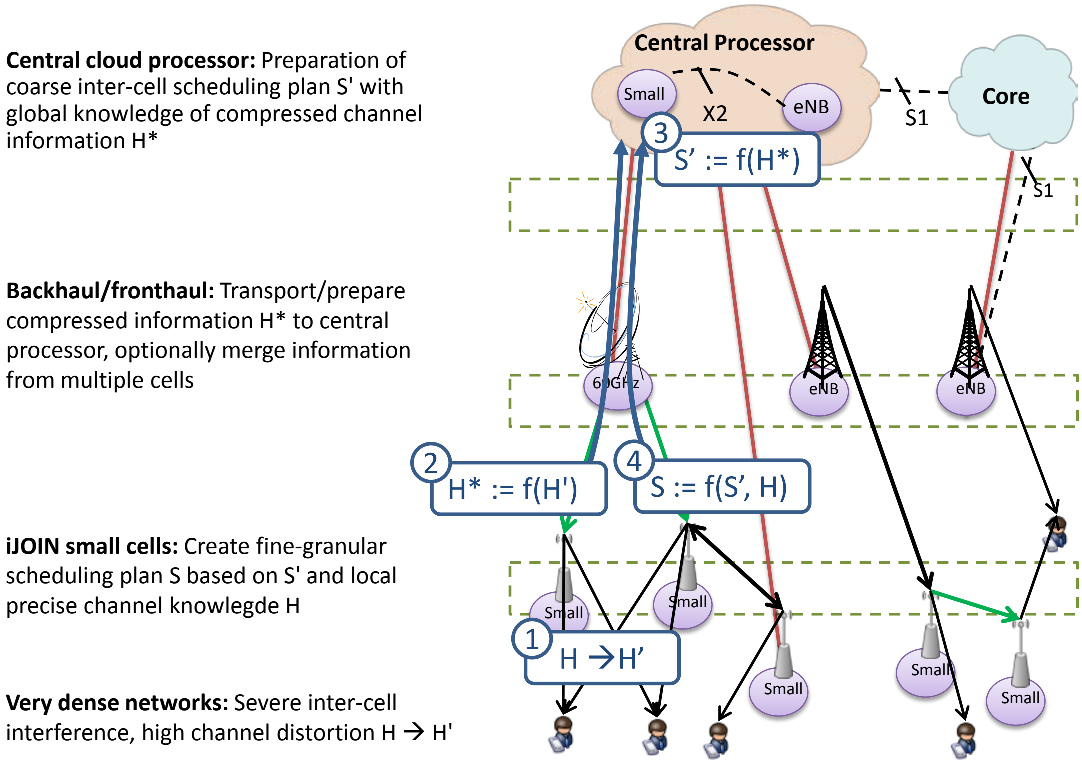
4.4.1 Scenario Description

The computational resources of cloud platforms enable centralized processing of complex tasks with global knowledge which would not be possible in base stations. Semi-deterministic scheduling exploits these resources by shifting the computational load partially into the cloud, thus enabling the creation of a global scheduling plan for very dense small cell deployments. This is necessary to combat the severe inter-cell interference caused by short inter-site distances in such a scenario.

The challenges for semi-deterministic scheduling are two-fold:

- First, to identify the maximum achievable performance considering constraints on computational resources and backhaul. For example, if the backhaul delay is high, the channel may change significantly before channel information arrives at the central processor. Therefore, the computation needs to be based on averaged or compressed information, leading to more coarse/long-term scheduling plan.
- Second, to develop actual multi-level scheduling algorithms with in-network processing to exploit centralization gains in cloud considering backhaul constraints in network edge. Here the challenge arises to identify the minimum amount of signaling which is required to pass the channel state information to the central process, to determine the optimal schedule, and to provide the scheduling decision to the individual base stations.

Figure 4-4 describes the basic principle of semi-deterministic scheduling in more detail.



Central cloud processor: Preparation of coarse inter-cell scheduling plan S' with global knowledge of compressed channel information H*

Backhaul/fronthaul: Transport/prepare compressed information H* to central processor, optionally merge information from multiple cells

iJOIN small cells: Create fine-granular scheduling plan S based on S' and local precise channel knowlegde H

Very dense networks: Severe inter-cell interference, high channel distortion H → H'

Figure 4-4: Semi-deterministic, hierarchical scheduling

4.4.2 Assumptions

This CT assumes the existence of the J1 and J2 interfaces towards the RANaaS platform and between iSC, respectively, in order to exchange channel state information (compressed and non-compressed). The CT is most suitable for very dense small cell deployments in order to achieve high coordination gains due to interference mitigation. Furthermore, it is assumed that an appropriate protocol between iSCs and the cloud platform is in place for transport of the compressed channel and scheduling information.

Table 4-9: Assumptions of CT 3.4: Computation complexity and semi-deterministic scheduling

Assumption	Description
A.4.1	J1/J2 interfaces
A.4.2	Very dense networks
A.4.3	Protocol to transport scheduling / channel information between small cells and cloud

4.4.3 Technology Requirements

This CT requires that the channel distortion metrics are measurable at the UEs/iSCs, and that the backhaul is delay/capacity limited.

Table 4-10: Requirements of CT 3.4: Computation complexity and semi-deterministic scheduling

Technology requirements	Description
R.4.1	Channel distortion metrics are measurable at UEs/eNBs
R.4.2	Backhaul delays follow definition in [TR 36.932]

4.4.4 Mapping to iJOIN Architecture and Objectives

This technology candidate mainly addresses the iJOIN objectives area throughput by reducing/mitigating interference and exploiting diversity gains. The scheduling functionality is split between cloud platform and small cells. It is assumed that both J1 and J2 interfaces are available and capable of transporting channel measurement data as well as scheduling information.

4.5 CT 3.5: Cooperative RRM for Inter-Cell Interference Coordination in RANaaS

4.5.1 Scenario Description

We consider a dense deployment of local RAPs, which operate on the same bandwidth to improve the spatial reuse. Such a technical solution leads to high co-channel interference, which results in limited performance.

RAPs are inter-connected through a backhaul, which is characterized by limited capacity and finite latency. Furthermore, they are as well connected to an iNC, which may enable~~s~~ higher coordination with limited overhead and delay.

Cooperation enables the implementation of ICIC mechanisms, which can improve transmission robustness and maximize the network capacity.

Moreover, the cellular network can exploit the iJOIN RANaaS architecture to flexibly implement ICIC functionalities either in a centralized or a distributed fashion.

One candidate interference mitigation solution will exploit an exchange of information on neighbouring cell to enable a reliable estimation of the co-channel interference with a limited overhead.

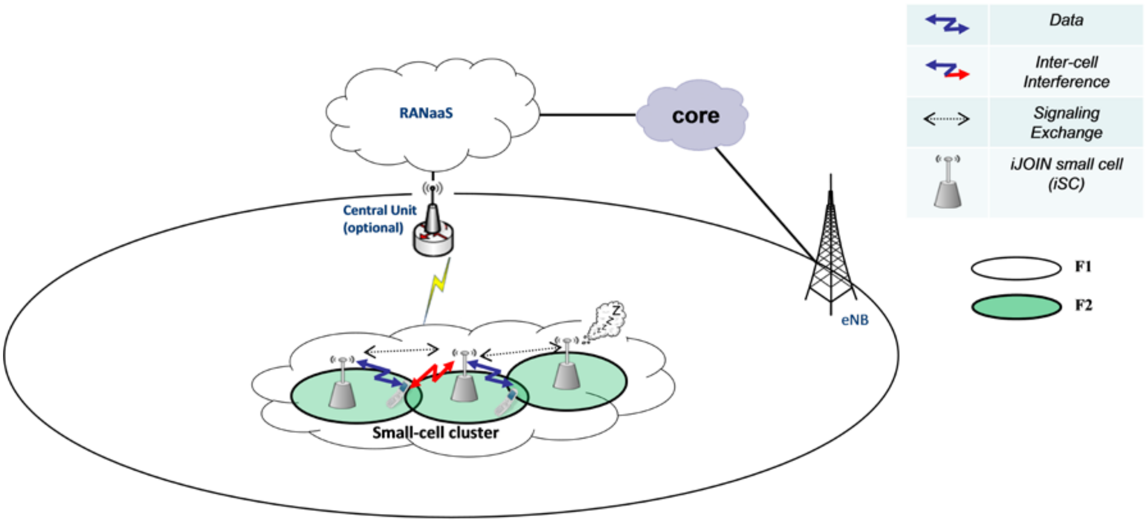


Figure 4-5: Inter-cell interference coordination between iSC

4.5.2 Assumptions

iSCs are assumed to be associated to a local orchestrator (i.e., the iNC node), which manages a cluster of iSCs and connect the iSCs to the core network / RANaaS platform.

J2 interface is assumed to enable exchange of information in a cluster of iSCs as well as the iSCs and their iNC. Its content will be investigated.

Table 4-11: Assumptions of CT 3.5: Cooperative RRM for inter-cell interference coordination in RANaaS

Assumption	Description
A.5.1	Area-based iNCs to cover a multitude of dense small cells for Interference / Mobility Management purposes
A.5.3	J2 link between iSCs and the iNC
A.5.4	J2/X2 link amongst neighbouring iSCs
A.5.5	Large number of iSCs in a local area
A.5.6	Finite backhaul capacity

4.5.3 Technology Requirements

Synchronization amongst iSCs is required at frame level to enable ICIC mechanisms.

Table 4-12: Requirements of CT 3.5: Cooperative RRM for inter-cell interference coordination in RANaaS

Technology requirements	Description
R.5.1	Synchronization between iSCs

4.5.4 Mapping to iJOIN Architecture and Objectives

By introducing novel interference mitigation techniques for dense small cell deployment, iJOIN will fully exploit spatial reuse gains. This will enable to increase the offered data rate in cellular networks with respect to current standards without the need to use additional frequency resources.

4.6 CT 3.6: Assess and Increase Utilization and Energy Efficiency

4.6.1 Scenario Description

Measurements in operator networks reveal [70] that 20% of all base stations carry 50% of the overall traffic. The main reason for this phenomenon is a wide deployment of macro-cells for high coverage, and the network dimensioning to peak traffic demands, meaning that a large fraction of deployed resources are underutilized.

In order to avoid over-provisioning of resources, a holistic view on utilization is taken to cover the whole network architecture from the cloud platform to the iSC. Correspondingly, relevant resources can be categorized along the two dimensions of resource type (e.g. radio, hardware, etc), and the network entity where the resource is provided and consumed (e.g. iSCs, backhaul, etc.).

Utilization efficiency is defined as a metric which expresses how well the utilized resources are used for a given performance metric. Therefore, high utilization efficiency means the following:

1. The system (such as a network) is highly utilized, and therefore not over-provisioned.
2. The system is capable to transform utilization efficiently into the desired output, such as cell throughput or other metrics.

One of the main objectives of iJOIN is therefore to increase utilization efficiency. It should be noted that utilization efficiency is closely related to two other efficiency objectives of iJOIN, which are cost and energy efficiency.

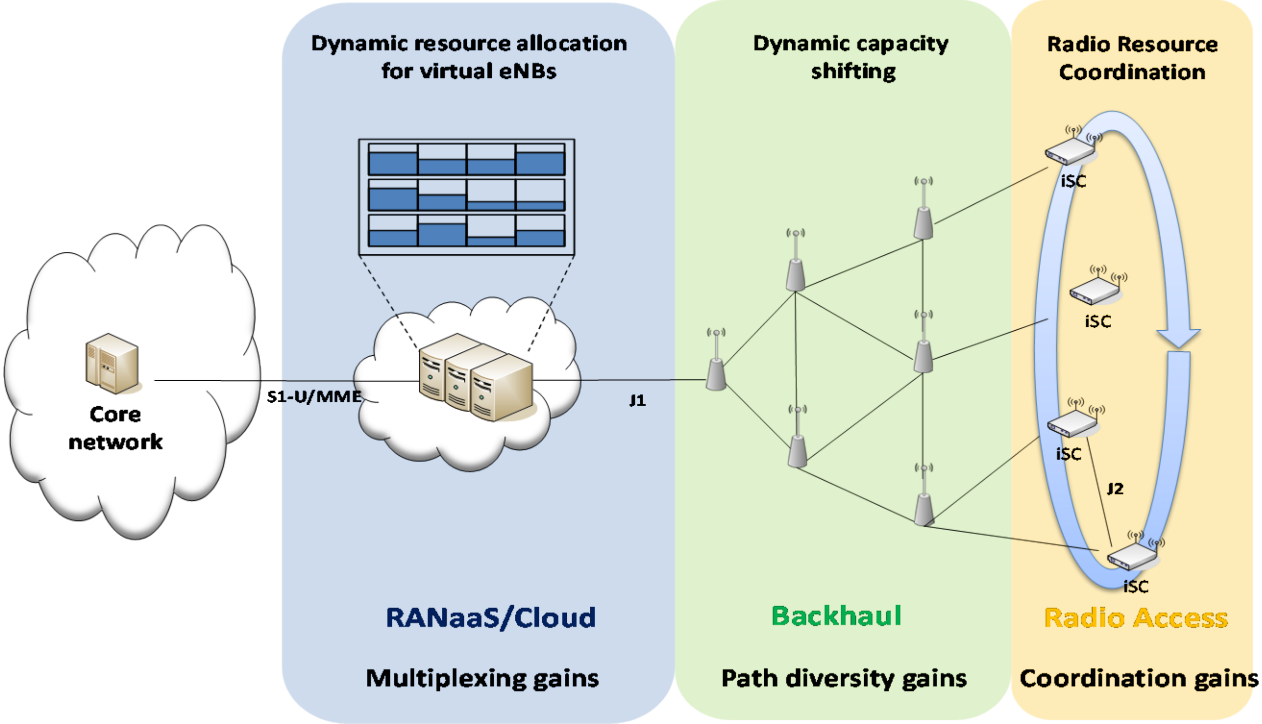


Figure 4-6: Resource allocation techniques in different iJOIN domains and their expected gains

Figure 4-6 shows an example how different resource allocation techniques in different iJOIN network domains can lead to different types of gains (e.g. multiplexing, diversity and coordination gains) which increase utilization and energy efficiency. The main goals of this candidate technology are as following:

1. Define and investigate metrics which capture utilization and utilization efficiency of a network implementing the iJOIN architecture. This includes different network entities and components, such as cloud resources, backhaul, and iSCs.
2. Perform analytical or simulative studies to investigate the potential benefit of RANaaS and joint access/backhaul techniques proposed by iJOIN regarding utilization efficiency. This could include, for example, statistical multiplexing gains for cloud resources due to centralization of iSC functionalities, or adaptation gains in the backhaul due to flexible shifting of link capacities according to the traffic demands.

The performance analysis will be based on appropriate abstractions of different technology candidates proposed in iJOIN.

On the **Energy Efficiency** side, the full scenario needs to be evaluated to make fair comparisons:

(1) The energy spent in the eNBs/small cells for the computation part (excluding radio)

(2) The energy spent inside the cloud for the servers in the datacenter hosting the computation related to the functions moved to cloud

(3) The energy necessarily spent as "due overhead" inside the cloud datacenter, i.e. the Air Conditioning, the UPS and other facility related consuming equipments (lights, etc).

The total energy spent in the cloud datacenter (sum of (2) and (3)) can typically be evaluated by multiplying the server consumption (2) by the Power Usage Efficiency (PUE) metric of the datacenter; efficient datacentres have PUE < 1.5, average PUE ~2, while PUE > 3 denotes a datacenter with bad energy efficiency.

Therefore, the final efficiency needs to consider the sum of all these components (if applicable). In the specific case for iJOIN, the comparison will be between:

A. The sum of the power for the cells with eNBs (1)

B. The sum of all power for the small cells (1), plus the power of the serves (2) times the PUE of the datacenter

It will be investigated how a global net energy efficiency improvement with iJOIN can be achieved.

4.6.2 Assumptions

This scenario assumes that certain candidate technologies are available and implemented to different degrees in a network which implements the iJOIN architecture, such as flexible RANaaS with dynamic and fine-granular resource allocation in the cloud platform, and dynamic capacity shifting in backhaul.

Table 4-13: Assumptions of CT 3.6: Assess and increase utilization and energy efficiency

Assumption	Description
A.6.1	Flexible RANaaS implementation
A.6.2	Dynamic capacity shifting in backhaul
A.6.3	Dynamic and fine granular resource allocation in the Cloud

4.6.3 Technology Requirements

Technical requirements on the architecture, implementation and/or deployment will be identified during the further course of this work.

Table 4-14: Requirements of CT 3.6: Assess and increase utilization and energy efficiency

Technology requirements	Description
N.A.	none

4.6.4 Mapping to iJOIN architecture and objectives

This scenario addresses utilization efficiency, and indirectly cost and energy efficiency.

4.7 CT 3.7: Radio Resource Management for Scalable Multi-Point Turbo Detection

4.7.1 Scenario Description

The idea behind the scalable multi-point turbo detection principle is to increase the (aggregated) uplink throughput by improving the detection quality of the users. Indeed, turbo detection allows significant performance improvement by relying on the information exchange (extrinsic log-likelihood ratios) between the detection stage and the decoding stage in an iterative way [71]. This principle (derived from the turbo code [72]) has been straightforward extended to the single-user spatial dimension (MIMO) and to the multi-user context ([73] and reference herein). One drawback of such iterative processing is the computational cost which goes linearly with the number of streams per users and the number of users involved in the detection.

The use of the RANaaS platform to perform this burden computation could enable the use of the turbo detection of users attached to a small cell and/or attached to different small cells (hence multi point). However, such approach clearly needs the link between the small cells and the cloud platform (J1 link) to be sufficient in terms of bandwidth and latency. If this J1 link is not sufficient to support this physical layer split, it should be able to carry all resources needed for a centralised RRM enabling the turbo detection to be applied at each small cell level (hence scalable) on a reduced set of users. In both cases, the centralised resource management algorithm may decide which small cells and which users should be involved in case of a multi-point turbo detection process.

The goal of this study will be to identify the resources needed for such centralised RRM algorithm based on the J1 capacity/latency. If local turbo detection is chosen due to lack of J1 sufficient transfer capability, information exchange between the small cells through the J2 link (or an extension of the X2 link) may also be investigated.

To evaluate the performance, an indoor small cell deployment will be considered as shown in Figure 4-7, where possible functional split between the RANaaS platform and the flexible iSCs is highlighted (to be refined after further investigations). This split is based on the J1 interface (High Quality, Medium Quality, Low Quality related to the bandwidth/latency capability of the link).

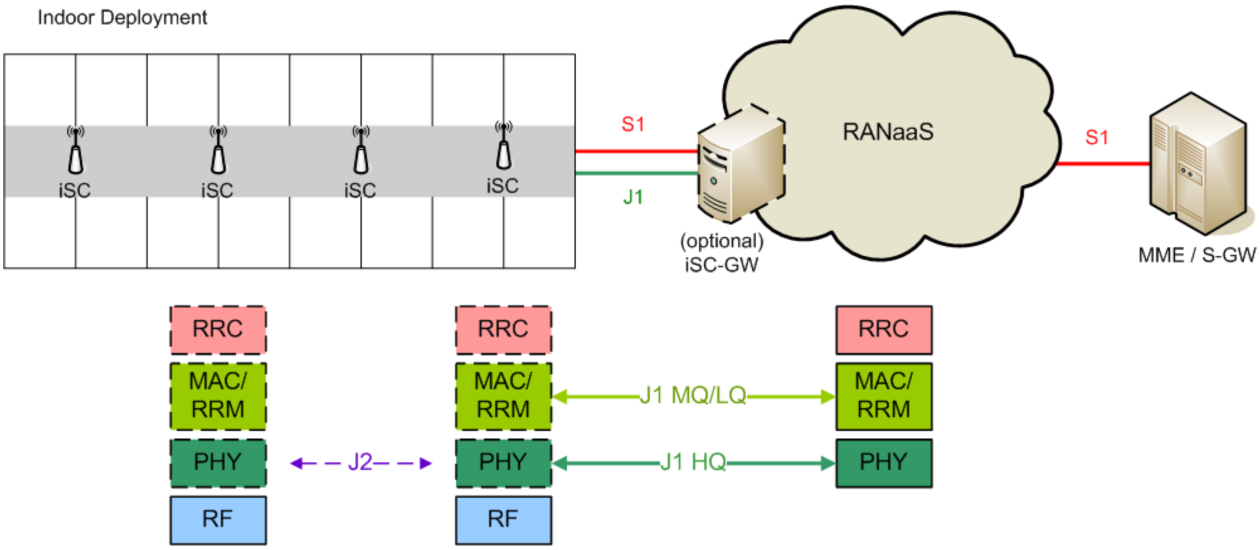


Figure 4-7: Scalable multi-point turbo detection investigation context

4.7.2 Assumptions

Small cells are assumed to be physically connected to the core network / RANaaS platform, either directly (independent backhaul) or through a “local” gateway (shared backhaul).

J1 interface presence is assumed between small cells and the RANaaS platform. “Logical” J1 interface goes through the “physical” small cell backhaul. Its content will be investigated: rawI/Q, soft values, control information, resource allocation mapping ... based on the small cell backhaul capability.

J2 or “extended-X2” interface between small cells may be present (J2 content to be defined based on the small cell/small cell link capability).

Table 4-15: Assumptions of CT 3.7: Radio resource management for scalable multi-point turbo detection

Assumption	Description
A.7.1	J1 interface between small cell and RANaaS platform. J1 uses the physical small cell backhaul.
A.7.2	J2 of X2-extended interface between iSCs
A.7.3	If a “local” gateway is deployed, link between the gateway and the iSCs should be high speed / low latency

4.7.3 Technology Requirements

Small cells must be time/frame synchronised, which should not be too difficult in a closed indoor deployment.

To stay LTE-compliant with up to Rel.11 UEs, the processing dedicated to the turbo detection (and not the radio resource management part) should be done below 4ms (for the ACK/NACK response).

If deported to the RANaaS platform, this constraint requires that the J1 data transfer in both directions and the computation to be done within this time frame. Therefore, J1 interface should be very low latency for turbo detection processing of the data part. Its capacity will be a parameter (based on the information exchange).

For radio resource management, J1 interface latency could be relaxed (low/medium latency) due to the low mobility of the users. Its capacity will be a parameter but should support the RRM algorithm for selecting users scheduling based on feedback (to be defined).

J2 interface may be exploited as well. It should be very-low to low latency. Its capacity will be a parameter.

Table 4-16: Requirements of CT 3.7: Radio resource management for scalable multi-point turbo detection

Technology requirements	Description
R.7.1	<2ms up to <70ms delay on J1 interface
R.7.2	<2ms up to <30ms delay on J2 interface

4.7.4 Mapping to iJOIN Architecture and Objectives

This candidate technology addresses the iJOIN objective: area throughput, which should be increased by a better detection and spectrum utilisation. RRM will be performed within the cloud while the turbo detection processing will have a scalable implementation based on the J1 latency/bandwidth.

Other metrics may be improved with for instance the energy consumption (less error, meaning less retransmission attempts).

4.8 CT 3.8: In-Network-Processing for RX Cooperation

4.8.1 Scenario Description

The objective of the investigated In-Network-Processing (INP) techniques is to increase the user throughput, and therefore, also the area throughput. Correspondingly, the UE transmit power is intended to be reduced if the user throughput is kept unchanged.

In order to facilitate this, the UE is assumed to be in the range of several iSCs, with overlapping cells. The type of the iSCs is not fixed. These iSCs cooperate in the detection process by exchanging information with each other. This information can e.g. be raw symbols, LLRs, soft bits or decided, “hard” bits.

The available inter-iSC links have to be parameterised and announced to the involved iSCs and the controlling entity, possible in the RANaaS, in order for the distributed processing algorithm to adapt to changing topologies. The same holds for information from the RRM that has to respect the necessities and consider the impact of the distributed processing, e.g., that a UE is not associated to a certain cell, but a group of iSCs, and therefore its effective access link has “virtual” properties.

Furthermore, INP allows for a flexible split of the receive processing. The cooperative detection takes place either centralised “in-cloud” or decentralised, depending on backhaul (J1) and J2 capabilities. This decision is made by a management entity to adapt dynamically to the current state of the network.

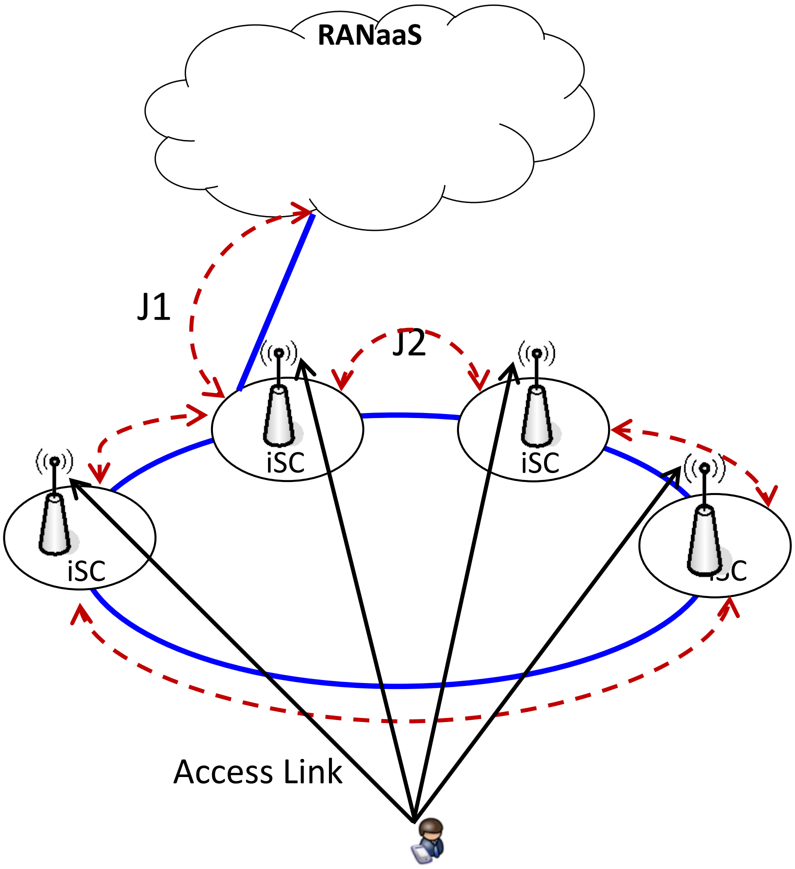


Figure 4-8: A UE is served by several iSCs, cooperating through In-Network-Processing

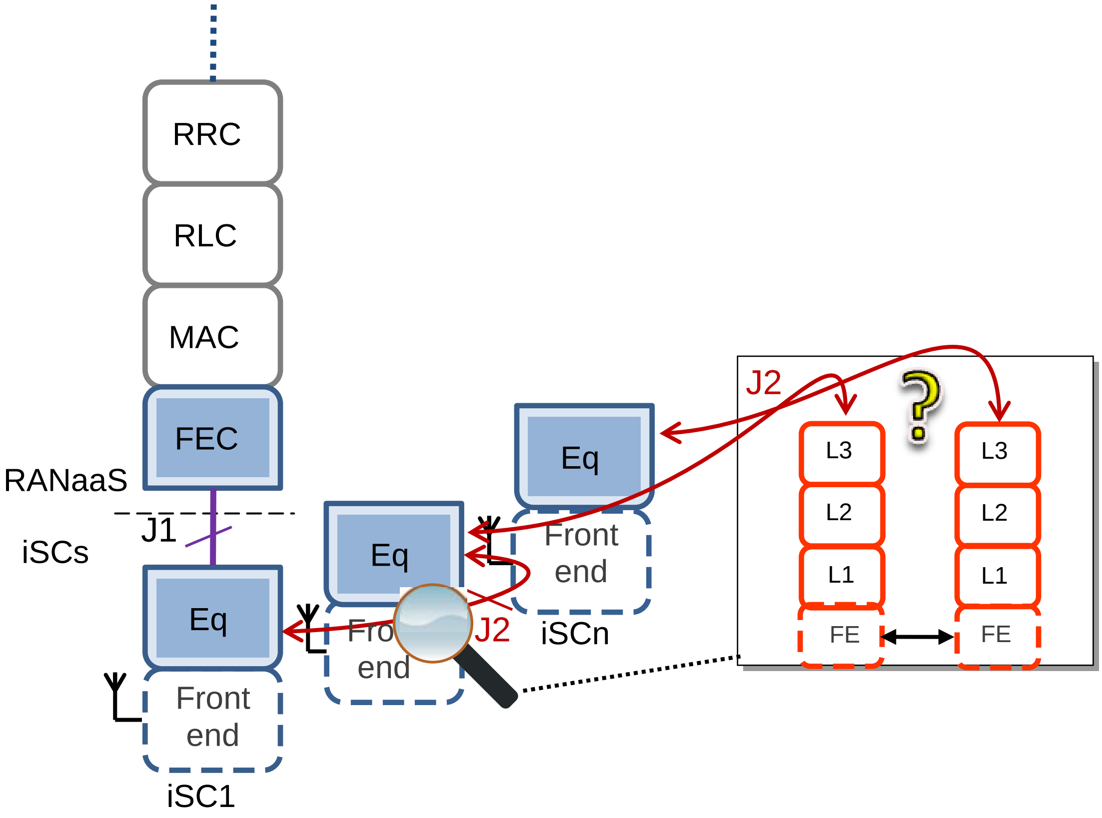


Figure 4-9: Illustration of the functional split in the scenario of In-Network-Processing for RX cooperation

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4.8.2 Assumptions

We assume that iSCs may have arbitrary connections to the core network or with each other.

There is assumed to be a J1 interface available between RANaaS and iSCs, since it is required for centralised processing ("in-cloud", one extreme of the functional split): Information on receive signals has to be carried on this logical interface (either raw samples, LLRs, or hard decided data). The underlying physical link does not need to be specified, as long as the properties of the logical link are known.

Furthermore, we assume a J2 interface between iSCs to be available for decentralised processing: Also on this logical link information on receive signals (see above) has to be carried. Its properties are also known.

Table 4-17: Assumptions of CT 3.8: In-Network-Processing for RX cooperation

Assumption	**Description**
A.8.1	Area-based iNCs to cover a multitude of dense small cells for coordination purposes.
A.8.3	Large number of iSCs in a local area
A.8.4	Limited backhaul capacity
A.8.5	Backhaul links may be independent and have different characteristics
A.8.8	Protocol to transport scheduling/channel information between small cells and cloud
A.8.9	Interface between iSC - iNC
A.8.10	Flexible RANaaS implementation
A.8.13	If a "local" gateway is deployed, link between the gateway and the small cells should be high speed / low latency
A.8.14	J1 interface between RANaaS and RAPs is available, its parameters are known.
A.8.15	J2 interface between RAPs is available, its parameters are known.

4.8.3 Technology Requirements

J1 and J2 are required to expose a very low latency, since in the decentralised case, several iterations of the In-Network-Processing Algorithms need to be carried out per received UE frame, and in the centralised case with processing in the RANaaS, the resulting delay for forwarding the raw receive signals into the RANaaS should be kept as low as possible. Links carrying management and signalling information have relaxed latency requirements.

Furthermore, all iSCs are required to be synchronised perfectly, since the distributed algorithm needs to run synchronously on all involved iSCs.

Although the INP algorithm is able to adapt to varying conditions, delay and bandwidth parameters of the J2 links are required to change only slowly, to reduce the required amount of signalling.

Table 4-18: Requirements of CT 3.8: In-Network-Processing for RX cooperation

Technology requirements	Description
R.8.1	J2 (and J1) have to be very low latency
R.8.2	Synchronization of iSCs

4.8.4 Mapping to iJOIN Architecture and Objectives

The main iJOIN objectives addressed are:

- Increase of area throughput: The use of a distributed receive processing results in an improved joint detection of several users and therefore a reduction in effective interference. This allows for an increase of area throughput.
- Reduction of power consumption: With reception through several iSCs in parallel, the required transmit power of the UE to achieve a certain performance can be reduced, therefore increasing battery life and consequently, reducing the power consumption.

In-Network-Processing allows for a flexible shifting of functionality, i.e. receive processing, between the iSCs and the RANaaS and therefore actively supports the flexible functional split.

4.9 CT 3.9: Rate Adaptive Strategies for Optimized Uplink Transmissions

4.9.1 Scenario Description

In a dense network of small cells connected to core network through heterogeneous backhauls, where many users are present, completely decentralized radio resource allocation and fixed/dedicated backhaul utilization may be highly sub-optimal. Fully centralized dynamic scheduling which takes into account the varying channel conditions and user requirements may be too messy to realize as this would require enormous control signalling both on the access and backhaul network which actually might surpass by far the effective gains coming even with ideal scheduling. The techniques studied here would make the active users provide a low rate feedback of their channel conditions. The proposal would be to do the radio resource assignments as per the users demands and if the backhaul is capable of carrying this flow to the core. Backhaul assignments must make sure that application dependent capacity and latency constraints are satisfied.

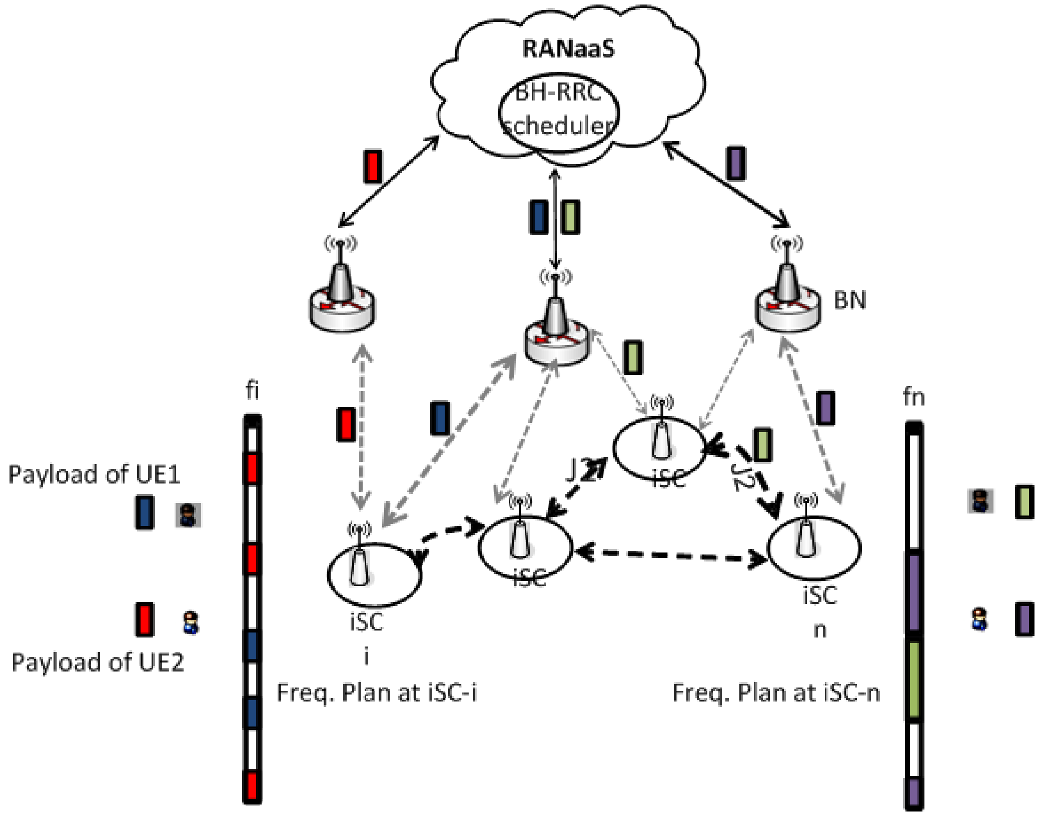

Figure 4-10: Uplink optimized scheduling of radio and backhaul resources

Figure 4-10: Uplink optimized scheduling of radio and backhaul resources depicts an exemplary situation for the proposed candidate technology. Many users are simultaneously being served by iSCs. The central scheduler sitting in the RANaaS would make sure the radio resource and backhaul allocation so as to optimally fulfil the users' requirements. For heterogeneous backhaul situations, when the backhaul is not able to carry a users' traffic, it does not make sense to allocate this user a large chunk of radio resources. This reasoning applies verbatim to the dual setting of constrained radio resource situation. Central scheduler is assumed to know the users' traffic demands and it may also obtain (partial) knowledge of users' instantaneous channel conditions through limited rate feedback. Backhaul topology and limitations in terms of capacity and latency are known at the central scheduler. Based upon this information, it does radio resource assignments to active users and optimal backhaul scheduling for the corresponding traffic flows. As a function of iSC capabilities and connecting backhaul links, the algorithm also indicates the network nodes how to do the functional split.

4.9.2 Assumptions

This scenario would assume the strict presence of low latency J1 interfaces linking small cells to RANaaS entities. Similarly the links connecting the iSCs, J2, would be assumed to have reasonable capacity and low latency. The presence of J2 links is not mandatory but would provide an extra level of flexibility not only for information exchange between iSCs but also when backhaul to one iSC is not of sufficient capacity and it may haul its' traffic through a neighbouring iSC. To be able to do the scheduling, the users' traffic demands are assumed to be known at the central scheduler a-priori.

Table 4-19: Assumptions of CT 3.8: Rate adaptive strategies for optimized uplink transmissions

Assumption	Description
A.9.1	J1 links with known capacity and latency
A.9.2	J2 links with known capacity and latency
A.9.3	Users' traffic demands are known.
A.9.4	Mild or slowly varying radio channel conditions

4.9.3 Technology Requirements

In the proposed technology candidate, iSCs are assumed to be synchronized. The other very important requirement is low latency for backhaul links. This is in particular important for J1 links which connect iSCs to RANaaS entities. This requirement can be relatively relaxed for J2 links.

Table 4-20: Assumptions of CT 3.8: Rate adaptive strategies for optimized uplink transmissions

Technology requirements	Description
R.9.1	iSCs are synchronized
R.9.2	Low latency backhaul links

4.9.4 Mapping to iJOIN Architecture and Objectives

- Which iJOIN objectives are addressed and how is this achieved?
    - Objective 1 is addressed with the increased throughput coming as an outcome of optimized scheduling.
    - Objective 4 is addressed as well when scheduler would choose the proper resources to avoid underutilization or overflow of traffic.
- Which functional entities are located where in the iJOIN architecture?
    - The proposed BH/radio resource scheduler is centralized. The processing might be split as a result of scheduler decision as a function of traffic requirements and backhaul available possibilities.
- How is the functional split realized?
    - Functional split is dynamic ranging from decentralized one when backhaul is unable to take the traffic load (and small cells are operating as if they are conventional cells) to partially centralized when traffic and backhaul conditions allow the processing to be done in RANaaS nodes.

5 Consolidated WP3 Assumptions and Requirements

5.1 WP3 Architectural and Technology Deployment Assumptions

The following table defines architectural and technology deployment assumptions per technology candidate. Using this list the preliminary iJOIN architecture is derived, the specific requirements will be investigated / derived based on this architecture.

Table 5-1: Consolidated WP3 assumptions and requirements

Assumption	Description	1	2	3	4	5	6	7	8	9
A.3.1	Availability of a logical controller for the joint RAN/BH optimization	x	o	o	x	o		x	o	
A.3.2	60GHz link between small cell eNB - iNC	o								
A.3.3	Large number of iSCs in local area	x	x	x	x	x		x	x	x
A.3.4	Limited backhaul capacity	x	x	x	x	x			x	
A.3.5	Heterogeneous backhaul with different, independent link characteristics	o	o	o		o			x	x
A.3.6	Required data rate may be higher than the available cell capacity due i.e., to cell load and backhaul capacity	x	x	x		x				
A.3.7	FDD based small cells for channel feedbacks and data transmission			x				x		
A.3.8	Protocol to transport scheduling/channel information between small cells and cloud				x			x	x	x
A.3.9	Interface between small cell eNB - iNC	x	o	o		o		x	o	x
A.3.10	Flexible RANaaS implementation						x	x	x	x
A.3.11	Dynamic capacity shifting in backhaul						x	x		
A.3.12	Dynamic and fine granular resource allocation in the RANaaS platform						x			
A.3.13	If a “local” gateway is deployed, link between the gateway and the small cells should be high speed / low latency							x	x	
A.3.14	J1 interface between RANaaS and iSC with known parameters				x			x	x	x
A.3.15	J2 interface between iSCs with known parameters	x	x	x	x	x		x	x	x

<u>Legend</u>

“x”	mandatory assumption
“*“	optional choices for implementation candidates (“OR”)
“o”	optional assumption; this not-mandatory feature may lead to improvements
“ “	not assumed for the TC

6 Functional Split

The following tables summarize the main requirements and the potential benefits that can be achieved by bringing some of the layer 2 functionalities to the cloud. This information will help in the future to perform the functional split in the iJOIN architecture between the functions carried out in the iSCs and the ones performed in the RANaaS.

Table 6-1: Initial assessment of functional split impact (part 1)

Functionality	Computational Needs	Centralizaction Cost/Impact	Centralization Benefits	Computational Diversity	Latency req. on interface
Split U-plane/ C-plane	O(#cells)	High (impact on eNB architecture)	High (e. g. central RRM)	TBD	High (if following frame creation)
Cell selection and Reselection	O(#UE)	Low	Low	TBD	Medium
Ciphering/security	O(#bearers)	Medium	Medium (no need for additional security)	Follows #bearers	Low
Quality of service mgmt	O(#bearers)	Medium	High	Follows #bearers	Medium (mostly applied to RT)
RRC connection handling	O(#bearers)	Low	Medium	Follows #bearers	Medium (RB control)
Mobility Control in RRC_CONNECTED	O(#UE, #BS)	Low	Medium	Low-Medium	Medium (during HO)
RoHC	O(#bearers)	Medium	Medium	Follows #active QCI = 1 bearer	Medium (mostly applied to RT)
In-sequence and duplication detection	O(#buffer size)	Low	Low	-	Low
ARQ	O(#retransmissions)	Low	Medium	Depends on CQ	Medium
Segmentation, Reassembly, … of SDUs	O(#bearers)	Low	Low	Follows #bearers	Low
(QoS) Scheduling	O(#network load)	High	High	High	High (TTI)
Inter-cell RRM	O(#network load)	High CAPEX (mainly for fiber deployment)	High	High	Low to medium

The table details the following properties for each functionality:

- **Computational needs:** defines whether the functionality is computational intense or not. This is done using the O(X) notation which defines in which parameters the computational needs scale.
- **Centralization cost and benefits:** defines whether the functionality provides gains if it is centralized or not and the cost associated to that centralization.
- **Computational diversity:** specifies whether a functionality's complexity may be time-variant (or varies in another parameter such as number of users, CSI, …). In this case, it may be possible to exploit this diversity to load balance computational needs in the RANaaS entity.
- **Latency requirement on interface:** specifies the latency requirements on the interfaces between the functionality and those functionalities that either deliver or receive data to/from the functionality.

Table 6-2: Initial assessment of functional split impact (part 2)

Functionality	Bandwidth req. on interface	3GPP impact	Link reliability req.	VeNB impact	C-plane / U- plane
Split U-plane/ C- plane	Medium/High (control plane / ol option)	Yes	High	architecture	n.a.
Cell selection and Reselection	Medium (control plane)	Yes (currently UE located)	Medium	low	C-plane
Ciphering/security	BW on PDCP layer	Yes (Kenb has to be known at RANaaS)	High (avoid bit errors)	Buffers, transport protocol, reliable link	U-plane
Quality of service mgmt	Medium	Yes (FFS)	n.a.	FFS	U-plane
RRC connection handling	Low (control msg)	No	High (c-plane messages)	low	C-plane
Mobility Control in RRC_CONNECTED	Low	Yes	High (avoid HO failures)	FFS	C-plane
RoHC	BW on PDCP layer	No	low	low	U-plane
In-sequence and duplication detection	Low	No	High	Medium (buffers/rel. link)	U-plane
ARQ	Medium	No	High (avoid retransmisions on air)	Medium (buffers/rel. link)	U-plane
Segmentation, Reassembly, … of SDUs	BW on the RLC layer	No	High	Medium (buffers, rel. link)	U-plane
(QoS) Scheduling	HIgh	No	High (if on UP path)	High (core function)	U-plane/c-plane
Inter-cell RRM	Depends on granurality	No	Medium	Depends on RRM approach	C-plane

The table details the following properties for each functionality:

- **Bandwidth requirement on interface:** specifies the bandwidth requirements on the interfaces between the functionality and those functionalities that either deliver or receive data to/from the functionality.
- **3GPP impact:** specifies if the centralization of the functionality would imply any change in the 3GPP standards.
- **Link reliability required:** indicates the reliability requirements on the interfaces between the functionality and those functionalities that either deliver or receive data to/from the functionality.
- **VeNB impact:** specifies the impact that this functionality may have in the deployment of the Virtual eNB.
- **C-plane / U-plane:** indicates if the functionality affects the C-plane, the U-plane or both of them.

7 Summary and Conclusion

In this report, the state-of-the-art of the main topics involved in the MAC/RRM design of iJOIN is presented. These topics include an introduction to the MAC aspects of Long Term Evolution (LTE), a thorough analysis of the radio access and backhaul solutions that can be applied to a very dense network with high interference level and non-ideal backhaul, and an overview of the main characteristics of cloud-RAN and cloud platforms. Based on this state-of-the-art, several promising MAC/RRM Candidate Technologies for the radio access and the backhaul networks are presented. These MAC/RRM Candidate Technologies enable a holistic design of radio access network and backhaul network and can be applied to the different common scenarios proposed in WP5. The common scenarios include: stadium, square, wide-area continuous coverage, indoor (airport/shopping mall). The assumptions and requirements of each CT are also explicitly mentioned. Finally, the consolidated assumptions and requirements for WP3 are presented.

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