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Final report on MAC/RRM state-of-the-art, Requirements, scenarios and interfaces in the iJOIN architecture

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Abstract

This report presents an overview of the activities carried out by Work Package 3 (WP3) during the first twelve 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 provided. Furthermore, candidate technologies for MAC and RRM which will be developed in future stages of the project are introduced. To contribute to the successful development of the iJOIN RAN architecture, we have elaborate a draft of the interfaces related to the proposed technical solutions and identified the functional placement in the logical architecture. Finally, we have described in details how the functional split paradigm could be implemented for different candidate technologies, and for three basic RAN functionalities, namely cell selection, inter-cell RRM, and segmentation/reassembly.

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Abbreviations

3GPP	3rd Generation Partnership Project
ABS	Almost Blank Subframe
ALU	Alcatel Lucent
AM	Acknowledged Mode
AMC	Adaptive Modulation and Coding
API	Application Platform Interface
ARQ	Automatic Repeat request
BBU	Base Band Unit
BCCH	Broadcast Control Channel
BCH	Broadcast Channel
BN	Backhaul Node
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
E-GTSP	Exact Generalized Traveling Salesman Problem
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
GPS	Global Positioning System
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
KPI	Key Performance Indicator
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
NSN	Nokia Siemens Networks
OBSAI	Open Base Station Architecture Initiative
OFDMA	Orthogonal Frequency Multiple Access
OPEX	Operational Expenditures
OSS	Operational Support Systems
PA	Power Amplifier
PaaS	Platform as a Service
PCCH	Paging Control Channel
PCell	Primary Cell

PCH	Paging Channel
PCI	Physical Cell Identity
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
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
UPS	Uninterruptible Power Supply
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
WSRM	Weighted Sum Rate Maximization

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: We give an overview of 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. Another important topic of this deliverable is the presentation of the MAC/RRM Candidate Technologies (CTs) that will be developed in the project. For each CT, its description, assumptions, requirements, and objectives are given. Furthermore, each partner has also presented preliminary methodology and foreseen gains related to their study.

In order to enable a full integration of our studies in the iJOIN architecture, we have identified the relations amongst the WP3 proposed CTs and the other WPs. Accordingly, we have defined primary interfaces the enable the exchange of information between CTs, other basic MAC functionalities, PHY layer, and upper layers. Moreover, we have investigated the placement of the WP3 functionalities in the entities that compose the iJOIN architecture.

We have also presented a preliminary investigation on the functional split paradigm: in particular we describe how this concept can be integrated in the state-of-the art RAN protocols. Cell selection, inter-cell RRM, and segmentation/reassembly functionalities are described and possible functional split analysed. Accordingly, we have given a qualitative analysis on the impact and the achievable gains due to the successful implementation of the functional split concept in the discussed LTE protocols.

2 Executive Summary

This report describes the main activities carried out by the WP3 during the first twelve 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. The general concepts of LTE protocol layers from MAC to RRC, is described, followed by an overview of main improvements introduced in Release 11 and 12 of LTE, such as carrier aggregation, coordinated multi-point, mobility in heterogeneous networks, and small cell enhancements.

Section 3.2 focuses on the state of the art for MAC/RRM at the radio access, including inter-cell interference mitigation in dense small cell deployments, carrier aggregation, cooperative transmission, link adaptation and multi-user scheduling, as well as dirty paper coding or interference alignment schemes. Moreover, Section 3.2.2 provides an overview of energy efficiency enhancements, categorized into short term energy-aware approaches which adapt the transmission parameters to the fast variations in the network, and mid-term schemes which adjust the system characteristics (such as the number of active small cells) to the daily traffic profile.

The main wired and wireless solutions for backhaul networks are analysed in Section 3.3, covering the main characteristics of copper and fibre backhaul, and wireless solutions spanning microwave radio links, 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, and millimetre wave radio in the ≥60 GHz band.

Section 3.4 describes the state of the art for cloud RAN, including the existing cloud RAN architectures developed so far by the industry, and existing protocols and APIs that can be used to connect the radio access points to the cloud data centre. The functional split between these entities is outlined in Section 3.4.3, while Section 3.5 is devoted to the state of the art for cloud platforms, focusing specially in its possible application for the iJOIN project.

Section 4 discusses the different MAC/RRM CTs in WP3, describing, assumptions, requirements, objectives and preliminary results. All CTs address at least one of the four objectives of iJOIN, which are area throughput, energy, cost, and utilization efficiency (see Table 2-1 for an overview).

Table 2-1: Main objectives addressed by WP3 candidate technologies

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

The CT descriptions contain assumptions and requirements, which have been harmonized between CTs and build the foundation for embedding the CTs into the iJOIN logical architecture. This is further described in Section 5, including the input/output parameters of each CT and the functional interaction within WP3 and across WPs. The functional architecture, together with the iJOIN logical architecture, is one of the major milestones towards an integrated toolbox of technologies which constitute the iJOIN approach (see Figure 2-1).

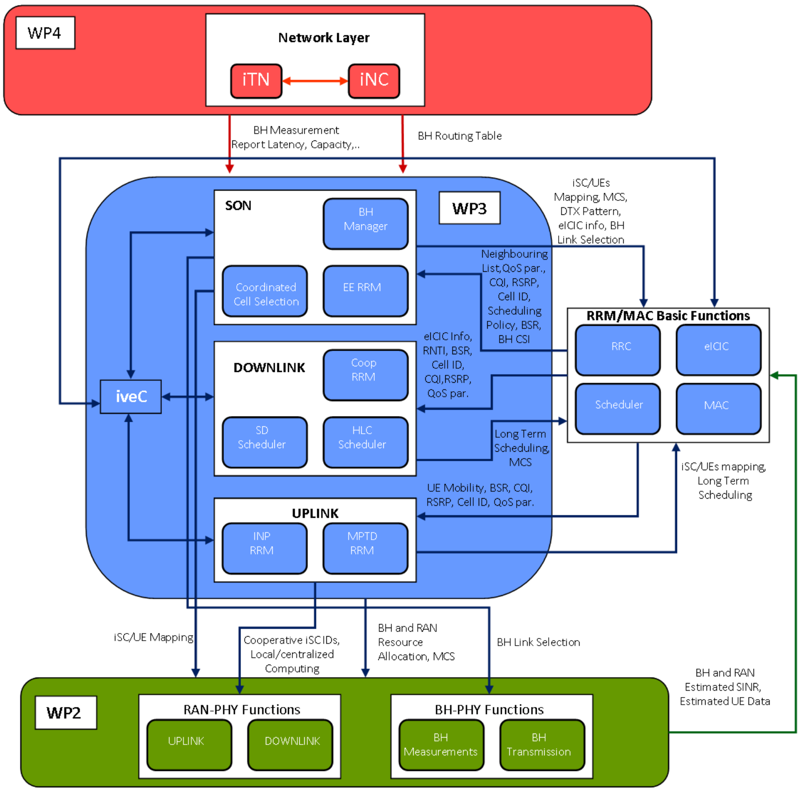


Figure 2-1: WP3 functional architecture.

The second major aspect of IJOIN, the functional split, is discussed in detail in sections 5.4 and 5.5. For each CT, the challenges, advantages, and potential benefits of different functional split options are discussed. Furthermore we investigate in detail how to realize the functional split for system functions which are essential for the radio access architecture on the example of cell selection, inter-cell RRM, and segmentation/reassembly protocols.

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 the multiple access technique, 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. 12. 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.

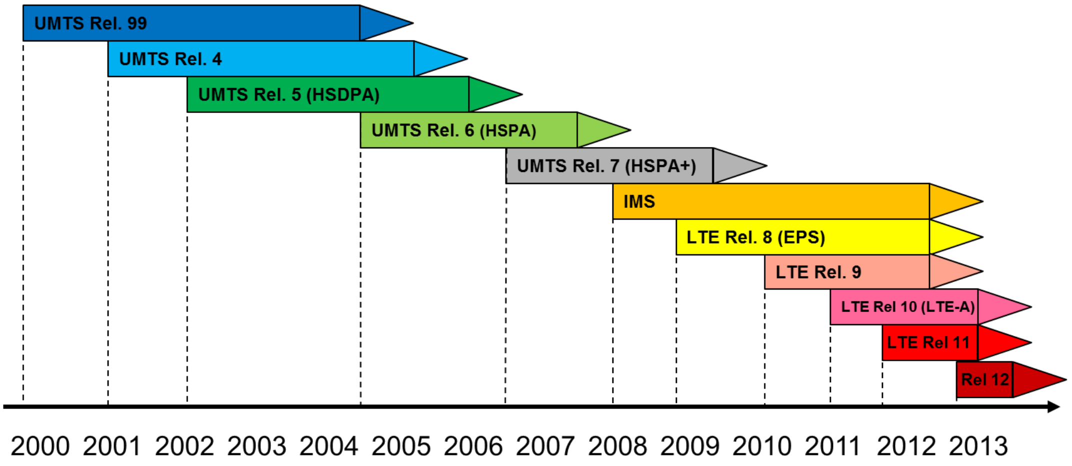


Figure 3-1: 3GPP releases until LTE Rel. 12.

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;

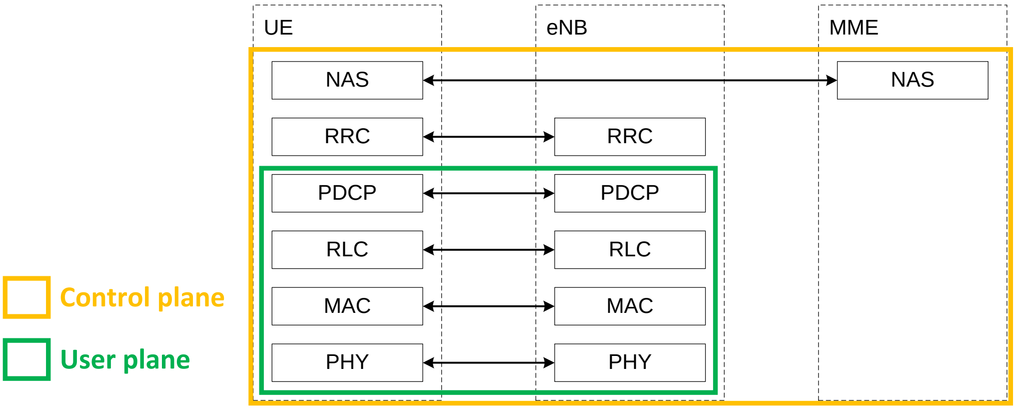


Figure 3-2: LTE control and user plane protocol stack [3].

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.

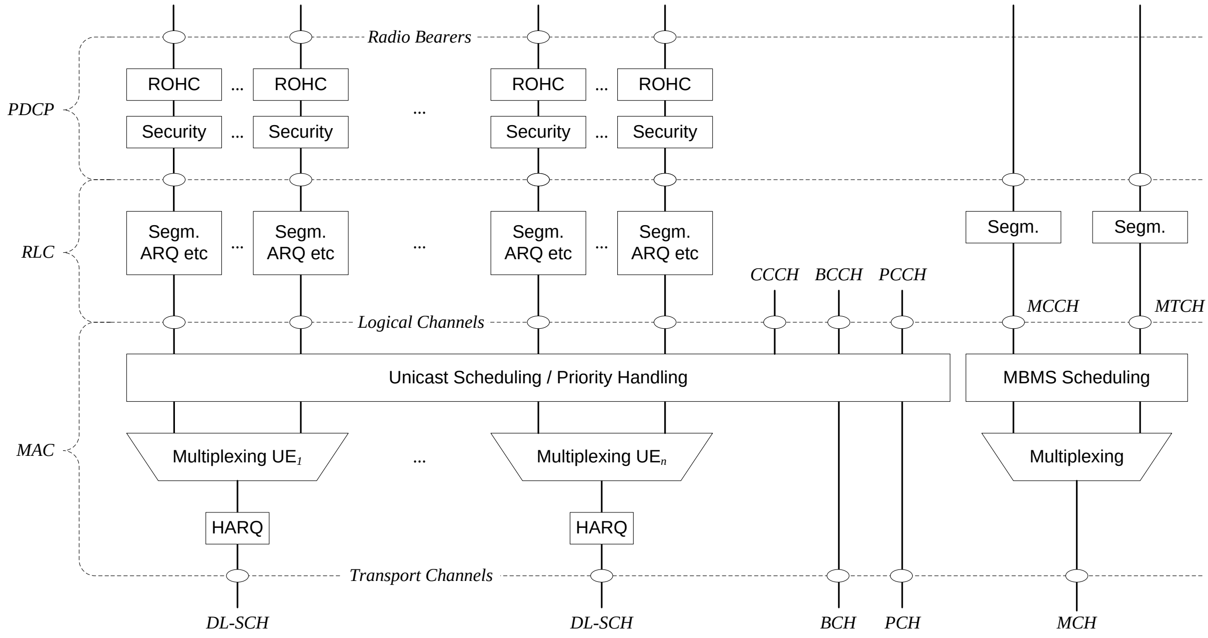


Figure 3-3: Layer 2 structure for downlink [1].

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.

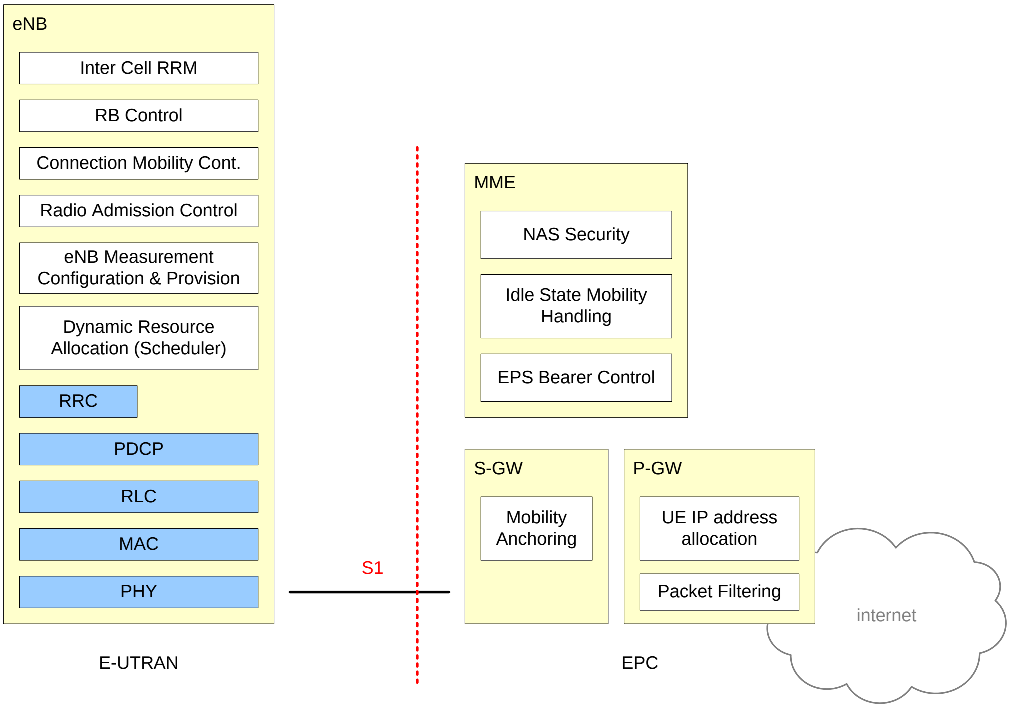


Figure 3-4: Functional split between E.UTRAN and EPC [1].

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. In this case, 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.

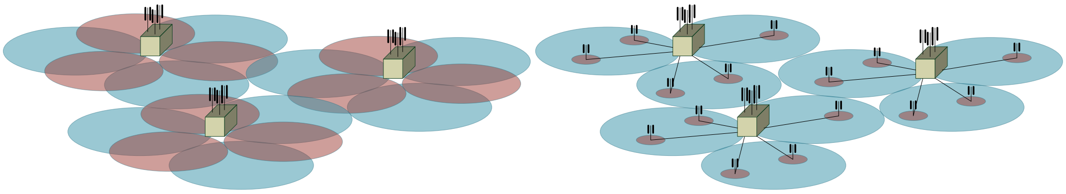


Figure 3-5: Two inter-band carrier aggregation scenarios with co-located cells (left) and RRHs (right) [9].

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: CoMP deployment scenario with remote radio heads and fibre backhaul [11].

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.

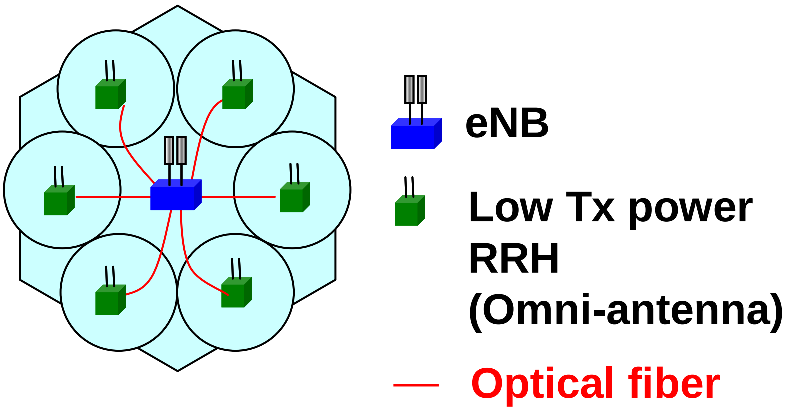


Figure 3-6: CoMP deployment scenario with remote radio heads and fibre backhaul [11].

A further topic was mobility enhancements for Heterogeneous Network (HetNet) deployments [12]. With the main objective of studying 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 that includes 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.

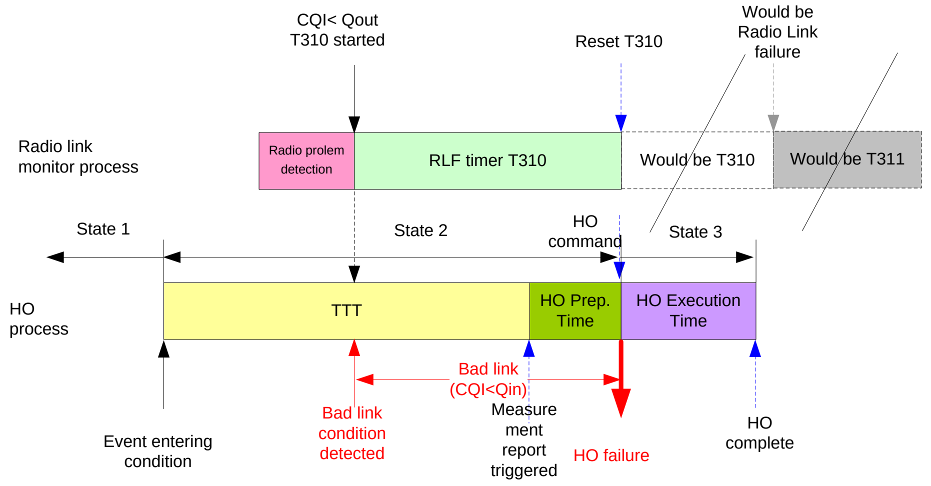


Figure 3-7: Hand-over failure modelling [12].

The impact of different data traffic patterns (e.g. packet sizes, packet inter-arrival times, data volume) has been studied in the work item “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.

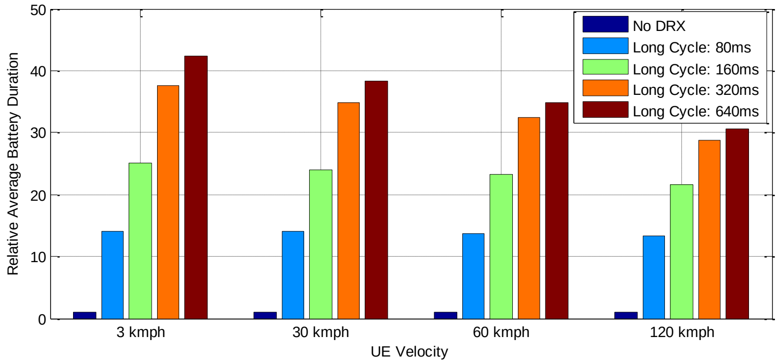


Figure 3-8: Impact of DRX cycles on battery duration [13].

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 were 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.

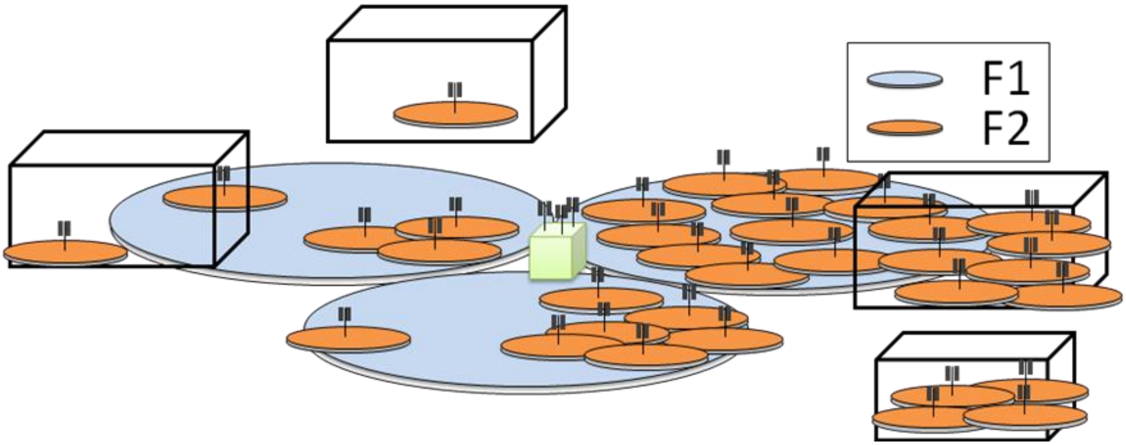


Figure 3-9: Deployment scenarios for small cell enhancements [15].

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

Work on small cell enhancements in 3GPP RAN groups has been split into physical layer aspects [16] and higher layer aspects [17]. Figure 3-10 shows the common scenario assumptions for evaluation based on the deployment scenarios described in [15]. It is assumed that small cells form a cluster for the purpose of interference coordination, and that coordination is performed decentralized either between small cells, or centralized by a macro cell. Ideal and non-ideal backhaul deployments are assumed.

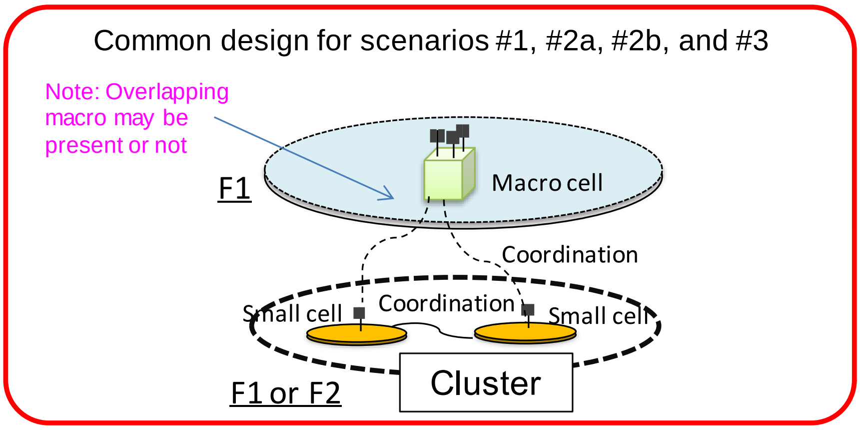


Figure 3-10: Small cell deployment scenarios for evaluation [16].

The following physical layer aspects are discussed in [16]:

- Mechanisms for interference avoidance and coordination among small cells. This includes small cell on/off schemes up to sub-frame granularity for interference coordination and energy saving, enhanced power control and use of ABS (Almost Blank Subframe), and load balancing/shifting methods.
- Mechanisms for efficient discovery of small cells and their configurations to cope with potentially severe interference on reference signals of densely deployed small cells, related larger UE efforts and cell planning for PCI (Physical Cell Identity) collision. Proposed mechanisms include reference signal interference cancellation, burst transmission schemes with low-duty cycles, and novel discovery schemes. Furthermore, it has been evaluated whether there is a necessity to extend PCIs due to an increased probability of PCI collision. It has been concluded that this is not necessary.
- Feasibility and benefits of radio-interface based synchronization mechanisms for TDD deployments. Synchronization by GPS (Global Positioning System) or synchronization over backhaul network is not always available for small cell deployments, e.g. for indoor deployments. Proposals include network listening, where a target cell monitors reference signals of the source cell for synchronization (see Figure 3-11), and UE-assisted synchronization.

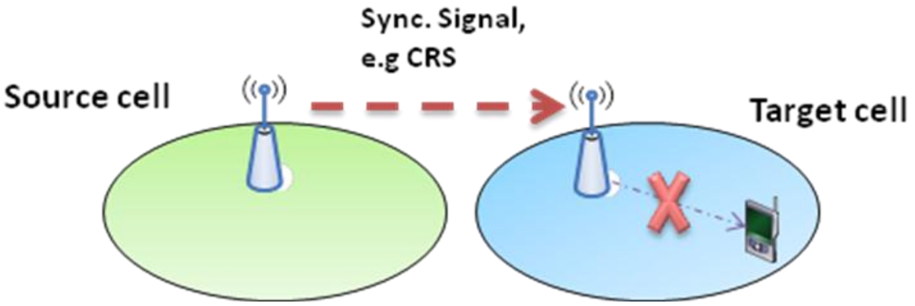


Figure 3-11: Network listening synchronization mechanism [16].

Challenges identified at higher layers include mobility robustness, UL/DL imbalance between macro and small cells, increased signalling load due to frequent hand-over, difficulties to improve per-user throughput in HetNet scenarios, and network planning and configuration efforts [17]. While mobility robustness was already addressed in [12], the other challenges have been documented and evaluated. Potential solution include dual connectivity, which refers to an operational mode where a given UE consumes radio resources provided by at least two different network points connected with non-ideal backhaul, similar to carrier aggregation. The main question to answer is how the user and control plane data is handled between the macro and small cell eNodeB. Different options for bearer splitting are proposed (see Figure 3-12), which have implications on the LTE protocol stack: the more the macro eNodeB takes over tasks (e.g. segmentation in RLC) from the small cell eNodeB, the higher the impact on existing protocol stack. Similar implications are discussed for C-plane (RRC) signalling.

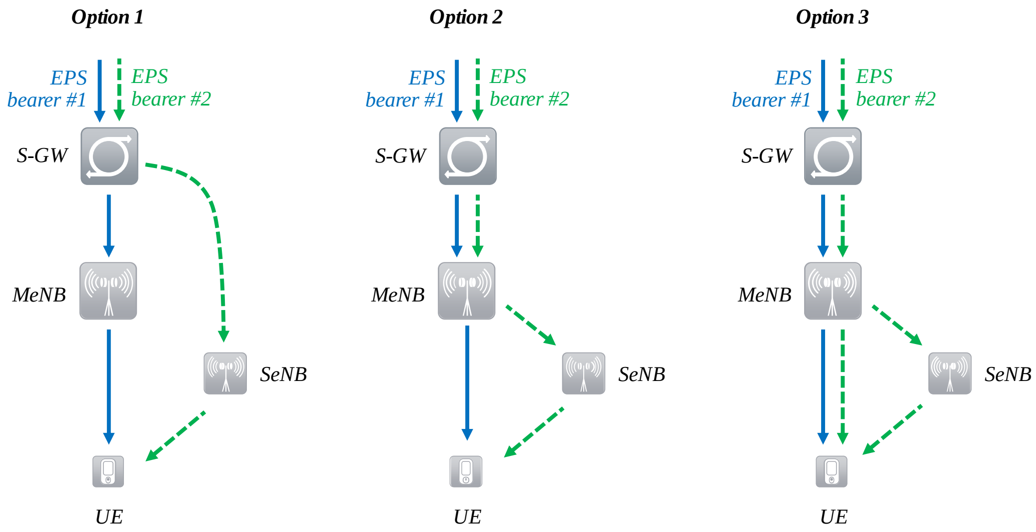


Figure 3-12: Bearer split options [17].

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

3.2.1 MAC/RRM for Enhanced Spectral Efficiency and Inter-Cell Interference Mitigation

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 [18]. Therefore, operators have complemented the macro networks with small cells that further reduce the path losses experienced by mobile users and result high capacity and data rate in areas covered by small cells. Another advantage related to this solution is the limited impact in terms of capital and operation expenditures associated with low power nodes [19].

However, due to their reduced range (from 10 to 100 meters) a dense deployment of small cells 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, like CoMP [26]. 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 unavailable 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 [20]. Other notable advantages come in terms of mobility management, support for operation in HetNets, improved coverage, and interference mitigation [21].

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 [22]. 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 3-13). 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 [23].

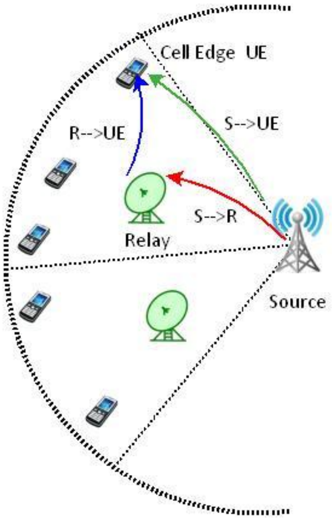


Figure 3-13: Cooperative transmissions through wireless relays.

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 [24]. 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 [25]. 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 [26]:

- 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 [27].
- Finally, in the dynamic point selection scheme, the eNB serving a given user can be changed, amongst the CoMP elements, at subframe level.

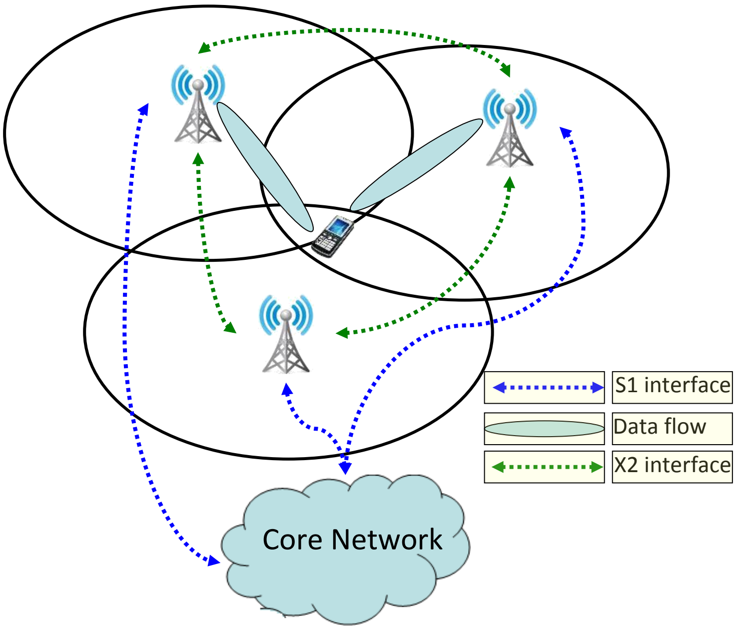


Figure 3-14: Joint transmissions in CoMP.

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 [28].

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 [29], 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 [30]:

- 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.

Interference Mitigation Techniques

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 [31].

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, where CA enables macro and small cells to operate downlink signalling on different CC, while data transmissions can be performed on same CCs.

Furthermore, eICIC exploits also time domain solutions [32]:

- 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, an eNB transmits only reference signals, no control or data signals; therefore data transmissions are also protected at costs of reduced spectral efficiency.

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 [33].

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 [34]. 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-linear 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 [35]).

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 [36]. Furthermore, there are four different architectures that can be used for implementing various SON use cases [37]:

- 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 and/or EM and/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 eNBs 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 [37], 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. 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, eNBs 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, stochastic theory, game theory, genetic algorithms, and swarm intelligence algorithms.

- Graph theory algorithms [38]: 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, eNBs are represented by nodes while edges indicate that two nodes are in the interfering range of each other (see Figure 3-15). In LCG, the vertex set represents active flows, while edges represent a contention between different flows.

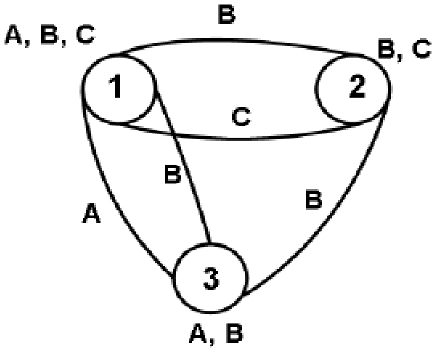


Figure 3-15: A NCG indicating channel availabilities and interference constraints.

- Stochastic algorithms [39]: 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 3-16). 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.

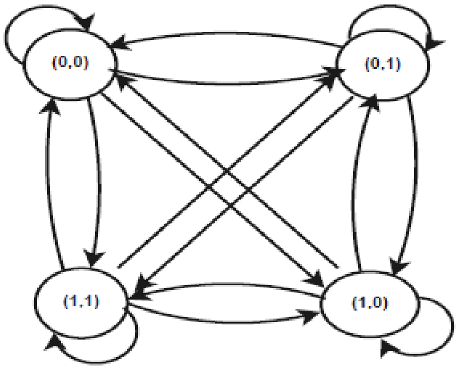


Figure 3-16: The Markov model representing channel state transition {0-idle; 1-occupied}.

- Game theoretic algorithms [40]: 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 $\Gamma = \langle N, \{S_i\}, \{u_i\} \rangle$. N is the set of game players, each send/receiver pair is an element of this set; S_i represents the strategy space (modulation and coding schemes, transmission power, antenna parameters, etc) of player i; u_i is the local utility function that models the scope of player i.

- Genetic algorithms [41]: 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 [42]: 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.

3.2.2 MAC/RRM for Enhanced Energy Efficiency

Future wireless networks require enabling mechanisms, which exploit the energy efficiency trade-offs to improve the network sustainability [43]. These approaches enable the cellular network to adapt its characteristics to load variations and avoid energy wastage while ensuring end-users QoS. Then, a first classification of such enabling technologies can be made by observing the time-scale, in which they operate. Fast adaptation mechanisms are implemented in short-time scale (from milliseconds to seconds) to reply to fast changes due to mobility, cell load, and wireless channel conditions. On the contrary, slower schemes operate on a per hours-basis in order to adapt the network characteristics to the traffic daily variations. In fact, load presents a regular pattern during the day [44], which can be used to predict average capacity request in a given geographical region. Moreover, each network energy saving technique can also be analysed with respect the domain in which it runs. Basically, we can identify mechanisms, which change the network configuration and parameters in time, frequency, or space domain. For instance, bandwidth adaptation operates in the frequency domain while small cell switch-off creates geographical hotspots.

Short time-scale

The cell data rate is characterized by short term variations, which depend on several factors such as the number of active UEs, the traffic types, and mobility. Therefore, fast adaptation mechanisms, which operate in the transmission time interval, are required to dynamically match the actual traffic demand and the cell available capacity. Cognitive Radio-based algorithms can be used to measure and predict cell load variations and adapt network parameters accordingly [45].

An intuitive approach consists in limiting the usage of transmission resources in the frequency, time, and spatial domains. 3GPP/LTE downlink implements an OFDMA air interface where OFDM symbols are organized into a number of PRBs consisting of 12 contiguous sub-carriers for 7 consecutive OFDM symbols. With a bandwidth of 10 MHz, 50 RBs are available for data transmission; however, LTE defines a set of transmission bandwidths (from approximately 1.25 MHz up to nearly 20 MHz) that can be selected according to the cell load. Using less frequency resources reduces the irradiated power and also limits the number of reference symbols: switching from 10 to 5 MHz can enable up to 3 dB of energy saving [46]. A more advanced scheme exploits an energy aware resource scheduler that concentrates the allocated RBs on a fraction of the available bandwidth [47]. Then, additional energy saving can be achieved by avoiding transmissions of reference symbols in data-free sub-carriers and also by adapting the operational point of the Power Amplifier (PA) to the new output power. However, this Bandwidth Adaptation approach is characterized by two main drawbacks: first, it reduces the benefits of frequency diversity, second it requires modifications in the standards to fast switch amongst different bandwidth configurations. In order to solve these issues, the EARTH project has proposed a Capacity Adaptation scheme [44], which, on the contrary, constrains the maximum number of RBs to allocate on the entire available bandwidth (see

Figure 3-17). This approach is transparent for the end-user and is able to exploit the frequency diversity; however, reference symbol transmission cannot be limited.

Energy saving in time-domain can be achieved by dynamically deactivating hardware components (such as the PA), when transmission is absent in a given frame [48]. The benefits of the discontinuous transmission (DTX) approach are limited by the transmission of control signal, which is required by the 3GPP standard even in absence of downlink traffic. However, this basic scheme can already achieve nearly the 50% of energy saying at the eNB [46]. In a more advanced approach, the Multicast-Broadcast Single Frequency

Network (MBSFN) frame, which is a new feature introduced in LTE to enable mobile TV broadcasting, is used to introduce longer sleep periods, since less signalling is transmitted in this frame. Finally, a more radical approach named as extended DTX proposes to completely remove reference symbols to enable further energy savings [47]. Hence, only synchronization signals and the broadcast signal are used in idle scenarios, and mobility measurements are performed on the synchronization signals. However, this approach requires standard modifications and it is not transparent for the UE, which may lose synchronization and also be unable to enter in discontinuous reception mode, which preserves the battery life [46].

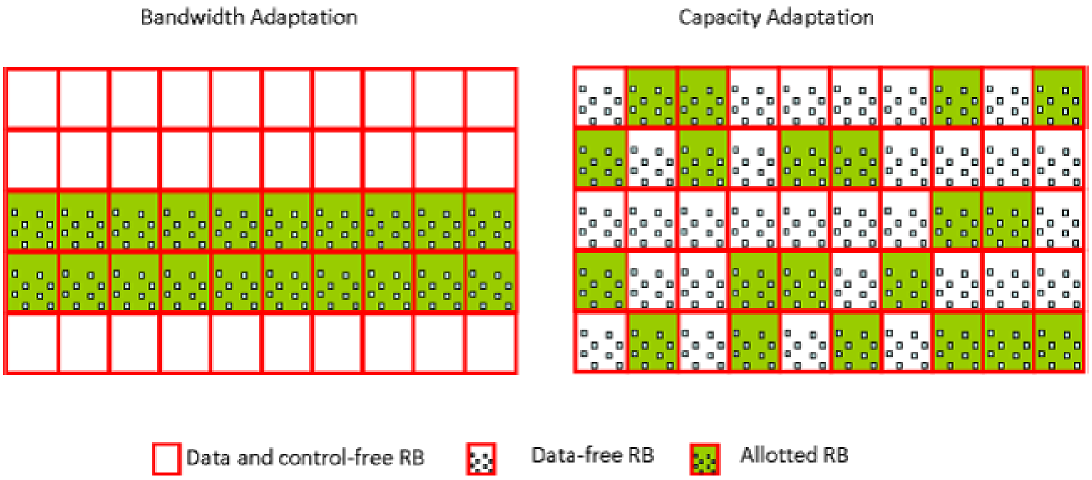


Figure 3-17: Scheduling pattern with Bandwidth Adaptation (left) and Capacity Adaptation (right) with 40% of cell load [47].

MIMO muting introduces energy saving in the spatial domain by dynamically adapting the number of active antennas in each cell [46]. As for the solutions that operate in the time/frequency domains, the main issue is to fast implement this adaptation mechanism (i.e., avoiding signalling exchange with UEs) while satisfying coverage and data rate constraints. Two main approaches are discussed in the EARTH framework to implement MIMO muting in a transparent way [47]: in the first case, the control signal for muted antennas are not transmitted, accordingly, neighbouring UEs will perceive these signals as in deep fade. In the second scheme, the signal corresponding to active and muted antennas are added together and transmitted by only a physical antenna. Then, these signals will be seen as correlated at the end-users.

An alternative approach to MIMO muting is to use a very large number of antennas at eNBs to operate in a limited energy per bit region. This idea, named as massive MIMO, originates from the linear relation between the ergodic capacity and the minimum value between the number of antennas at transmission/reception sides [49]. However, the benefits of MIMO systems strongly depend on the availability and robustness of CSI of all transmission links. In practical scenarios, CSI is affected by interference, delay, and user mobility, and it is hardly perfect. Ng et al. have investigated the resource allocation problem (in terms of number of antenna, power, frequency resources, and data rate) at cellular eNBs characterized by a large number of antennas and they have also considered the effect of imperfect CSI [50]. The authors have showed that this optimization problem is non-convex, and to limit the complexity and latency, they have found and equivalent problem that can be solved with an iterative algorithm. Hence, based on shadowing and path loss information, eNBs adapt the resource allocation scheduling according to a policy that maximizes the cell EE. The authors have considered a single cell scenario, however, intra-cell interference, due to the sub-carrier reuse, affects the end user performance. Simulation results have showed that high number of antennas is always beneficial from a capacity perspective, even with imperfect CSI; however, an exceedingly number of active antennas strongly increases the circuit power consumption, which may limit sustainability.

Medium time-scale

Here, we aim to discuss technologies that operate in mid-time scale and enable energy saving by adapting system characteristics to the slow variations of the network load. Traffic daily profile shows a regular pattern during the day with low load periods early in the morning, medium loads during work-time, and high data rate in the late evening; this profile holds also on a weekly time scale, however, weekends are characterized by lower traffic demands with respect to workdays [51]. Nevertheless, mobile networks are normally dimensioned to deal with peak time traffic and are under-utilized during the rest of the day. As previously discussed, eNBs are characterized by high power consumption even at very low load scenarios, and in these cases, limiting the number of simultaneously activated eNBs can result in notable energy saving. This energy saving approach can be implemented in three different uses cases [52].

- Inter-eNB energy saving;
- HetNet energy saving;
- Inter-Radio Access Technique (RAT) energy saving.

In the first case, when the mobile network is working in off-peak, load is concentrated in a small number of cells that remain active while a given set of base stations can deactivate transmission functionalities. This mechanism, also named as cell zooming [53], requires that eNBs, which stay active react to changes in the network layout to compensate the coverage losses (see Figure 3-18). This constraint presents different challenges in terms of inter-cell interference and coverage holes, which can be experienced in the area where deactivated eNBs are located.

Niu et al. introduces inter-cell cooperative transmissions to guarantee coverage and traffic requirements when cell zooming is implemented [54]. The selection of the set of active eNBs is modelled as a mixed integer programming problem, and hence, a suboptimal solution with limited complexity is proposed. The authors have showed that the proposed scheme gains up to 20% in terms of energy saving in light loaded scenarios; however, this result does not take into account the backhaul energy consumption, which is required for inter-cell cooperation.

In the HetNet scenario, small cells overlay the macrocell region to locally provide high data rate services. Therefore, in lightly loaded periods, energy saving schemes can be implemented to dynamically switch-off unnecessary low power nodes. To enable fast and reliable HetNet activity management, Ashraf et al. have investigated three different strategies that allow controlling the status of small cells [55]. In the small cell driven algorithm, the small cell is equipped with an energy detector that enables to sense the presence of nearby macro UEs. An indoor UE, which is served by the eNB, likely transmits with high power; hence it is easy to detect. Detection threshold is computed at small cell by estimating the path loss to the eNB, such that UEs located at its cell edge can be correctly detected. Henceforth, when a UE is detected, the small cell switches in active mode and whether the UE has the right to access the small cell, the handover process is initiated. Otherwise, the small cell reverts to the deactivated mode. This approach is characterized by limited complexity but required additional hardware (the sniffer) at the small cell; moreover, in high density scenarios, the aggregate energy received from different M-UEs can cause false alarm events that affect the detection reliability.

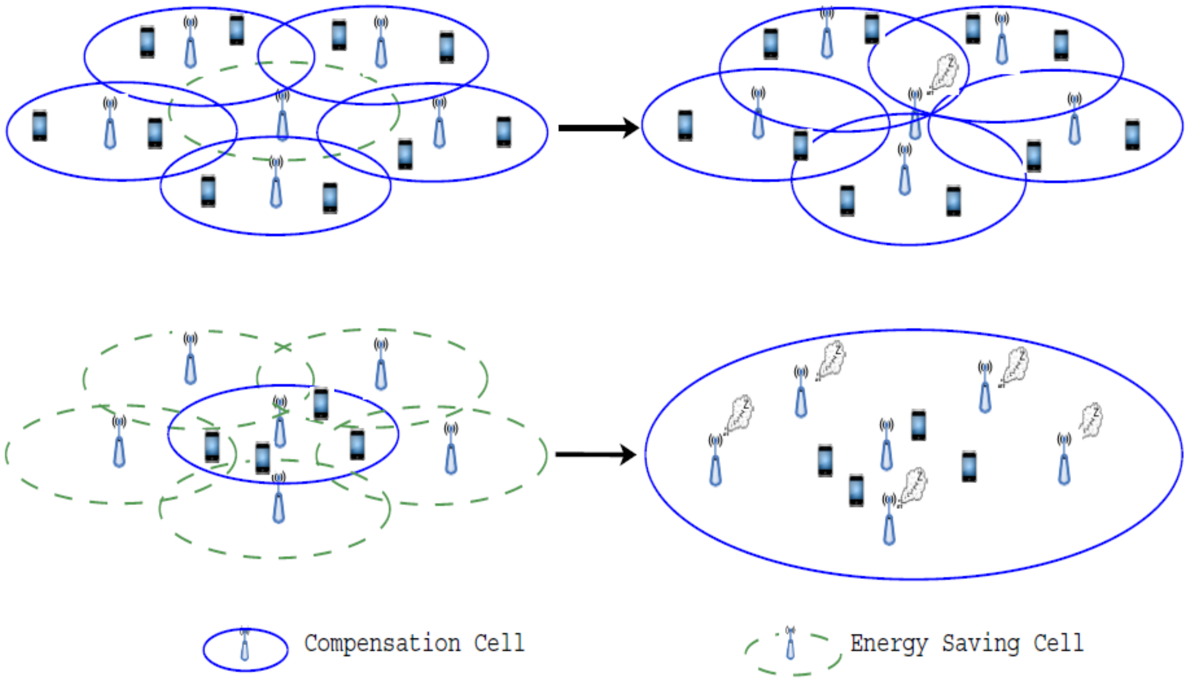


Figure 3-18: Cell zooming operations in mobile networks.

A more reliable solution assumes that small cells are controlled by the core network through the backbone. In highly loaded scenarios, the mobile network exploits the knowledge on the UE positioning, the cell locations, and the cell transmit powers to dynamically select the set of cells to activate.

The optimization policy, which selects the set of small cells to activate, depends on the completeness of this information, and partial or delayed feedback affects the system performance [56]. Alternatively, when location information is not available, the network may require to dormant hotspots to temporary switch on and transmit the pilot signal [52]; UE measurements from the small cells are reported to the network (i.e., through the macro cell eNB) and then used to decide which small cells have to be activated.

Different from the propositions above, the small cell activity can be controlled directly by the UE, which can periodically broadcast a wake-up message to find idle small cells in its range. Alternatively, a reactive scheme is feasible to save the UE battery consumption: in this case, the UE sends the wakeup message either when it experiences poor performance from the macro cell or when it requires higher data rate. A specific short range radio interface, like Bluetooth Low Power can be used to transmit the control message [57], however, such a blind wake-up algorithm is not supported in the current 3GPP standard.

All the previous schemes aim to dynamically manage the activity of small cell to create, ad-hoc hotspots in the macrocell region. However, an opposite, more flexible energy saving approach could be implemented if coverage constraints could be relaxed at low loads; in this case, high-power eNBs could also be switched-off and small cells kept activated, where required, to satisfy local user service requests [58].

The last uses case considers inter-RAT energy saving mechanisms. Nowadays, different wireless networks offer a variety of access options in a given geographical region. Legacy systems, such as GSM and UMTS, coexist with WiFi, LTE, and WiMAX, and in each of these networks the base stations are denoted by different coverage, capacity, and EE characteristics. When network cooperation is possible great energy saving is achievable by dynamically selecting those RATs and related base stations that can satisfy local service requests with the minimum energy consumption [59][60]. However, the overall network optimization is even more complex in this case, and it is fundamental to guarantee that vertical handover can be implemented amongst the selected RATs. To deal with these challenges, Bennis et al. have recently investigated a system with multi-mode small cells, which are able to simultaneously operate on both the WiFi and licensed bands [60]. In this scenario, the authors have proposed a distributed traffic offloading mechanism, in which small cells steer data flows between cellular and WiFi RATs, according to the traffic type, users QoS constraints, network load, and interference levels. In particular, in this framework, delay-tolerant applications can be offloaded to WiFi, while LTE is used to manage delay-stringent applications. Although this approach reduces the complexities in the inter-RAT offloading process, different wireless networks (like WiFi and LTE) may be handled by different providers; hence, new issues arise to balance energy saving and costs amongst different operators, which accept traffic originated from competitor subscribers.

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:

- Copper-based: Considering the copper-based solutions [62], 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 [62]. Moreover, T1/E1 lines provide timing and synchronization which are 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) [62]. 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 considerably rise.
- Fibre-based: Optical fibre can provide a multi-Gbps throughput connectivity that can be achieved using GPON (Gigabit Passive Optical Network) technologies [63]. 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 to the detriment of a relatively high Capital Expenditures (CAPEX) and a 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 [62].

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. Lower bands are preferred due to good radio wave propagation, albeit we may have less available bandwidth and long range interference [62]. 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 3-19 illustrates a sample deployment of 3 eNBs connected through microwave radio, where either LoS or near-LoS propagation is available.

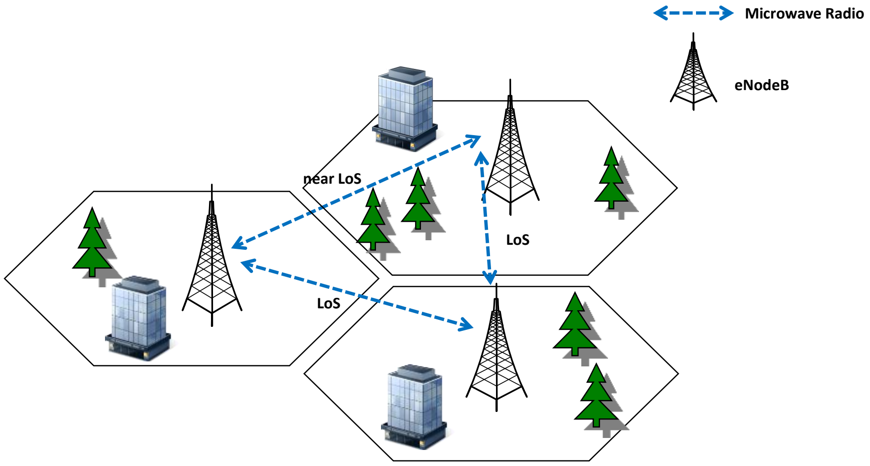


Figure 3-19: LoS and near-LoS microwave backhaul.

Wi-Fi

Wi-Fi (IEEE 802.11) [64] was initially designed for indoor connectivity and operates in 2.4 GHz and 5 GHz un-licenced bands. Further research advances in 802.11n [64], 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 [62]. By using smart mesh techniques together with the employment of adaptive antenna arrays for point-to-point connectivity, the complexity of the alignment and 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 [65]. FSO is a well-known technology from early military operations where beaming lasers were used for ship-to-ship communication [66]. The main drawback in this technology used to be its limited range and its dependency on changing weather condition. However, further advances in laser technology [66] enable FSO to provide simple, point-to-point high bandwidth communication. An example of point-to-point FSO is shown in Figure 3-20.

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 [65]. 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.

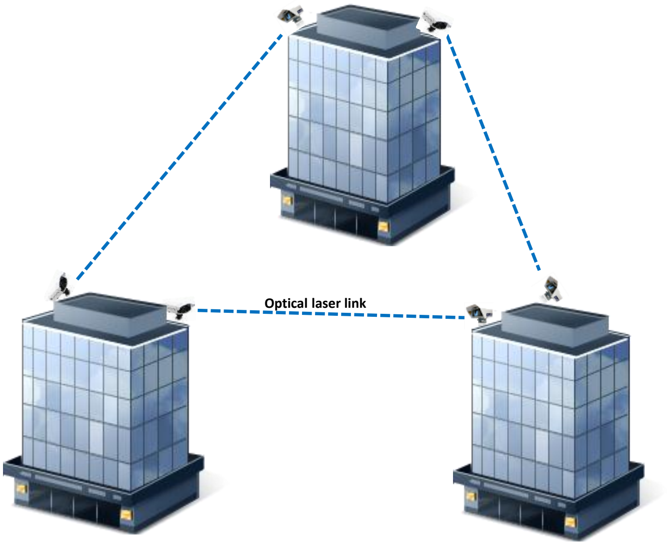


Figure 3-20: Point-to-Point FSO backhaul.

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 [62]. A sample deployment is presented in Figure 3-21: Satellite backhaul example.

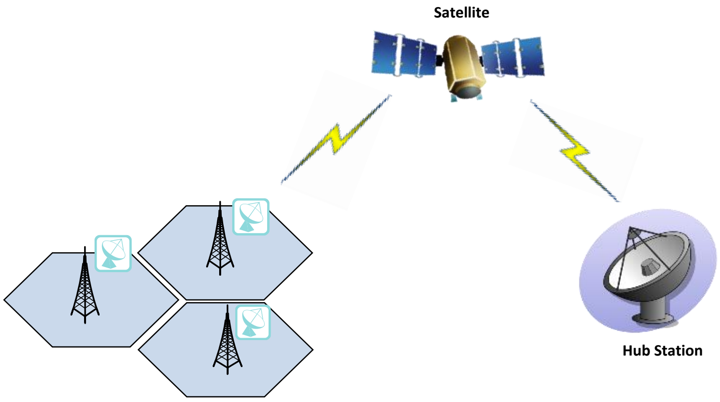


Figure 3-21: Satellite backhaul example.

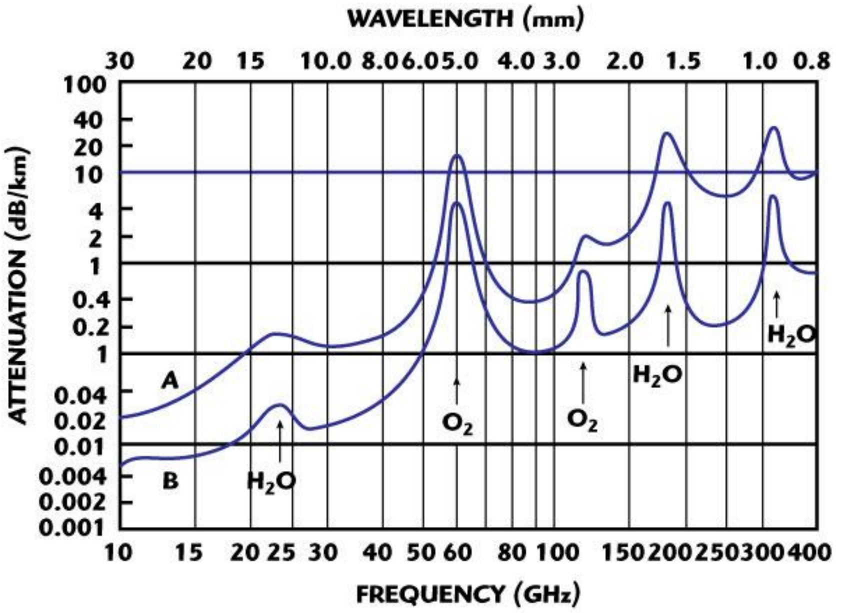
The advantages of satellite backhaul are its short installation time and flexible coverage. Furthermore, satellite communication can also deliver low installation cost due to its efficiency and flexibility as a one-to-many medium [62]. On the other hand, the main drawbacks are the cost of satellite communications 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” [67]. 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 [67].

It’s important 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 distance, 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.



Average atmospheric absorption of MMWs: (A) Sea Level: T = 20°C, P = 760mm, $H_2O = 7.5\ g/m^3$ (B) 4 km altitude: T = 0°C $H_2O = 1\ g/m^3$

Figure 3-22: Impact of oxygen absorption and rainfalls to signal attenuation in mmW radio.

3.3.3 Wireless Backhaul Topologies

Wireless backhaul is commonly deployed with the following topologies, depending on the scenario and requirements of the operator:

- **Point-to-Point (PTP):** 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 interconnected to form chain, tree or ring [63] 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.
- PTP links are an excellent way to establish connections between two sites and achieve high data transfer speeds, especially in the case when LOS is available and microwave / mmW radio is used. Traditional fixed service LOS microwave point-to-point links operate in licensed frequency bands (6 GHz and 42 GHz) with bandwidth ranging from 3.5 MHz up to 112 MHz. Due to the nature of the traffic carried by the mobile backhaul, traditional PtP LOS links are required to have high availability (e.g., 5 9's).
- **Point-to-Multi-point (PtMP)**: 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 [63]. The total hub capacity is shared among the underlying access points, hence statistical multiplexing gains can be realised.
- Wireless point-to-multipoint backhaul can be seen as an attractive solution mainly for the many low bandwidth requiring points in short distances, making it a good candidate topology for small cells. The management is central; hence it is easier and cost efficient to deploy. Comparing to point to point, the NLOS capability of PtMP is better due to the fact that wider antennas are used.
- **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 [68]. 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. Unlike PtP and PtMP topologies, mesh topology has the advantage to "repeat" the signal, and therefore extend the network coverage and provide increased reliability in adverse environments. A multitude of paths between source and destination nodes guarantees high network availability in case of node (or link) failures or poor channel conditions. This is critical for QoS assurance of real-time voice and video traffic.

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) [68]. 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 [68] 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 [68].

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 resource utilization by each node. The communication through multiple radios with multi-channel capabilities might cause inter-operability issues for a variety of MAC and routing protocols [68]. 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 [68]. 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 not only considers 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 backhaul nodes is balanced to prevent some access points from becoming bottleneck nodes.

T-Put vs. Coverage Trade-off:

One of the main objectives in a multi-hop wireless backhaul network is maximization of system’s capacity, which can be seen as the total throughput traversing a given set of nodes [69]. However the requirement for high data rate across the system can be restricted by the eNB range limitations imposed by transmission power. This can trigger the deployment of a dense eNB environment with low cost (wireless) backhaul connectivity [69].

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 [69].

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 [70]. 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 [70] 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 [70] enables the radio nodes to dynamically switch the channels, 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 [71].

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 [70]. Therefore a set of fixed radios can use a dedicated channel (CCA or VCA) and the rest set of radio nodes can dynamically change the utilized channel based on channel interference and 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 [72]: 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 jointly made in a central entity, taking into account the traffic load and the resource utilization.

- Distributed Routing and Centralized Scheduling [72]: In this case, routing is decided in each node in decentralized way through signalling exchange, and scheduling is performed in a central entity.
- Distributed Routing and Scheduling [72]: 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 [72]: 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 [73],[74],[75]. This approach advocates the shift of the baseband processing away from the physical location of the radiating elements 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

Cloud (or centralized) RAN architectures are in the focus of research and initial development in the telecommunication industry for some time. The following approaches are discussed in the literature:

- Alcatel Lucent (ALU) [76]: 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 [77], 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 [78]: 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.
- Intel is China Mobile’s partner in their C-RAN activities. Intel proposes the use of general purpose server processors for the cloud processing [79] and has demonstrated an LTE implementation with 4 emulated UEs [80].
- ZTE [81]: Chinese vendor ZTE claims to have demonstrated a working C-RAN installation providing 2G (GSM) service, using dedicated fibre links.
- Huawei [82]: 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 (NSN) [83]: 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 [84],[85]: 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.

- Ericsson has demonstrated an LTE proof of concept in Beijing [86], where a Remote Radio Head was connected to a Base Band Unit using a wireless point-to-point CPRI link in the E-band.

3.4.2 Existing Protocols/APIs

A significant number of existing architectures use the CPRI interface [87], which has been standardized precisely for the application of detaching RRHs from the base band processing unit. 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 [88], 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. However, it was demonstrated by Ericsson [86] that CPRI links can also be established using wireless point-to-point technology.

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 [89]. 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).

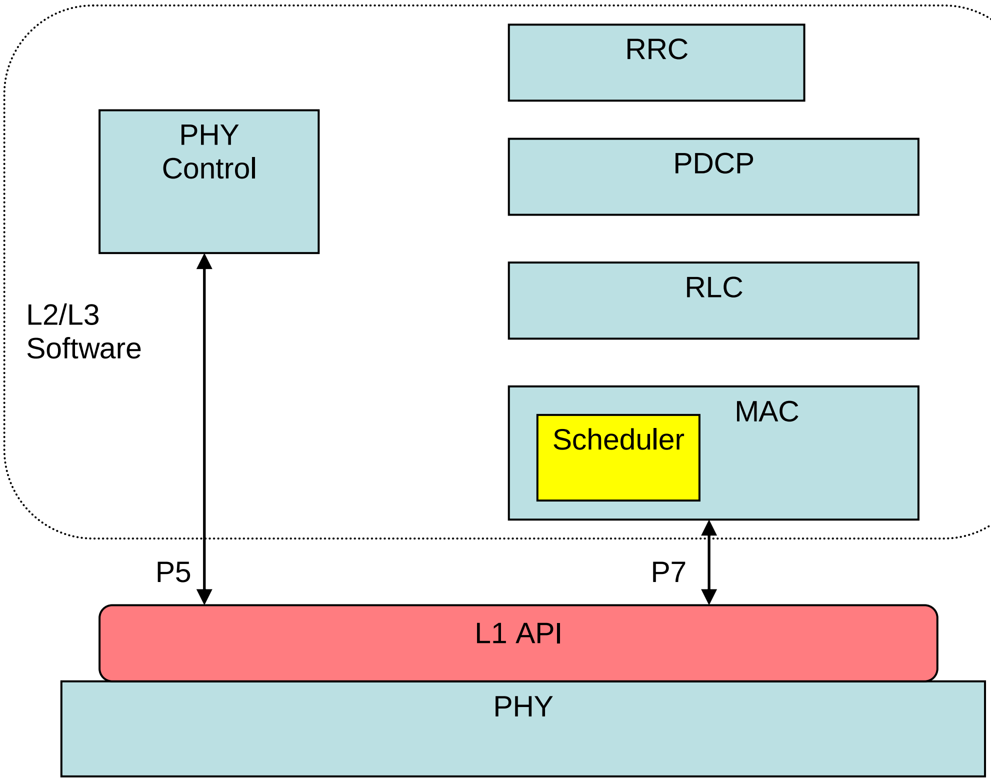


Figure 3-23: Interactions with the eNB L1 API as defined by the Small Cell Forum.

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

The deliverable D5.1 contains in Section 4.3 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 next paragraph, where we try to analyse the cloud “flavours” potentially most suitable to meet the needs of implementing a RANaaS architecture according to iJOIN requirements.

3.5.2 Cloud Computing models for iJOIN

A current research trend for mobile telecommunication operators concerns the deployment of OSS (Operational Support Systems) and some EPC Core Network components in Infrastructure as a Service (IaaS) private clouds [90], based upon industry standard hardware platforms. This shifting towards a general purpose IT infrastructure enables (only for selected components) the introduction of virtualization concept (deployment on virtual machines), the usage of standard operating systems and middleware enterprise software, and consequently the achievement of a better flexibility in the data centre resource usage, plus a related shrinking of IT costs. The choice of *private* cloud model is motivated by the need to retain better control on deployment, security and privacy management, and the ability to tweak the system performance for better accommodating the parameters demanded by shifting native E-UTRAN functions into the cloud platform.

The challenge for iJOIN is in fact further extending the cloud boundary to encompass a selected set of native E-UTRAN functionalities, making thus possible the realization of a related functional split. The requirements of iJOIN in terms of guaranteed performance, network throughput and QoS can reasonably be managed only in a private cloud, where resource allocation is more deterministically controlled, users are limited in number and capabilities, and load peaks can be grappled with in a more predictable way. This is in partial contradiction with the attribute “Shared” typically associated with public clouds [90], but can still be considered a valid case for a strictly controlled private deployment model.

Nonetheless, the variant of “virtual private cloud” can be an option. In this kind of model, 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) [90] 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) [90] model (once it has been refined, optimized and standardized) where the service might be offered by service providers even placed outside of the telco environment.

As far as the specific IaaS platform, the iJOIN concept should be transparent to it, i.e. the functional split should not be bound to a specific IaaS platform. For the purpose of iJOIN demonstrator, WP6 will select one of the currently available platforms (with potential preference for an open one).

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 gives an overview of the CTs and the iJOIN objectives they address.

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

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

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 for the small cells’ backhaul, 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 / mmWave) between iJOIN Small Cells (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). Here, BH link scheduling is performed in a locally centralized way (RANaaS). Assuming an indoor environment and 60GHz BH between iSCs, the purpose of this step is to dynamically identify which links have LoS connection. Here to mention that the 60GHz radio system relies on LoS transmission for achieving Gbps data rate and the communication can be easily interrupted by obstructions breaking the LoS link, which happens often due to the movement of people in a typical indoor environment.

In the multi-hop wireless BH consisting of small cells, routing information is required at the RANaaS entity from network layer (iNC) so as to identify which paths are selected (in larger time-scale) based on traffic load and energy efficiency criteria. Taking into account this information, our work focuses at the dynamic activation/de-activation of BH links using channel information.

Secondly, the next step is to identify flow(s) to be scheduled per link in a mesh network (targeting minimum QoS requirements besides the global objective). The iSCs (through iJOIN Transport Nodes (iTNs)) receive multiple data flows that are scheduled to be forwarded to multiple destination UEs. Considering the fact that the activated links are known for a given time by the previous step, each iSC has to schedule which traffic should forward to the assigned BH links so as prioritize traffic based on different QoS requirements.

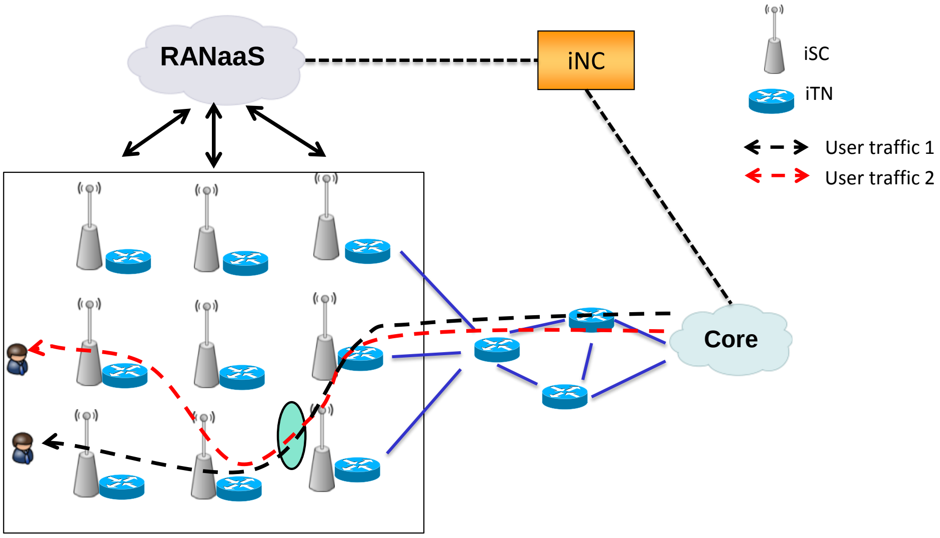


Figure 4-1: Backhaul link scheduling and QoS-aware flow forwarding.

4.1.2 Assumptions and Requirements

iJOIN Small Cells (iSC) can be connected through J1 to the RANaaS entity. This unit aims to manage a multitude of iSCs in a dense area so as to perform the BH link scheduling. Moreover, RANaaS entity should periodically receive routing information from iJOIN Network Controller (iNC). Also, the data flows are forwarded through the iJOIN Transport Nodes (iTN). Here we assume that an iSC can be co-located with an iTN for the forwarding of the data.

4.1.3 Expected Outputs

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

This CT investigates a scenario where iSCs are densely deployed to satisfy the demand of high data rate services of future wireless networks. In this scenario, we will introduce backhaul aware cell selection mechanism to enable network-wide load balancing and improve the overall network capacity.

Cell selection mechanism associates the mobile terminal(s) to neighbouring eNB(s), which are able to satisfy service request. This process is activated when a user has 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 eNBs and maintains a list of the neighbouring nodes (called the active set) associated with best detected signal, accordingly [91].

Hence, during the cell (re)selection process, the mobile sends a subscription request to eNBs 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 iSCs are located in the same geographical area [92]. The imbalance in the radiated power between eNB and iSCs does not permit mobile terminals to connect to the closest base station, 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 [93]. Range expanded UEs, may experience strong downlink interference; however, implementing range expansion jointly with ICIC results in improved fairness and network capacity [107]. Nevertheless, some studies have shown that using large values of range expansion bias, too many UEs may be associated to the same iSCs, and this might lead to overload issues [108].

To the best of our knowledge, there is a lack of solutions that investigate cell selection in scenario where the RAN can be constrained by the backhaul network. Conventionally, the air interface has been considered as the most limiting factor in terms of available resources and, therefore, the most important cause of congestion in wireless networks. Such an assumption is valid in the traditional macro cell-based system, where each cell site has the same backhaul capacity, transmission power, and average load. However, in HetNets, this is not always the case, due to the fact that the backhaul is one of the main technical challenges for small cells.

Therefore, novel cell selection schemes, which also consider the cell backhaul capacity, are required [94] [95].

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. In particular, in the following we will introduce a centralized and a distributed scheme that attempt to maximize the network capacity by jointly consider the radio access capacity and the backhaul capacity.

4.2.2 Assumptions and Requirements

The iSCs are assumed to be associated to RANaaS through the J1 interface, which enable centralized management in the wireless network. Also, J2 interface is assumed to enable direct exchange of information amongst neighbouring iSCs, and enable decentralized coordination when the centralized approach is not feasible. Furthermore, we assume that eNBs and iSCs are characterized by non-ideal backhaul links, which may be characterized by different latency and capacity. This may result in scenarios where required data rate may be higher than the available cell capacity due i.e., to cell load and backhaul capacity. Finally, synchronization amongst small cells is required to manage the cell (re)selection in a centralized way while satisfying QoS requirements.

4.2.3 Preliminary Results

First study:

Let denote by *U* the set of UEs and by *S* the set of eNBs that offers radio coverage in the HetNet under investigation. UEs are able to be served either by a eNB operating on F1 or by a iSC, which transmits on F2 (see Figure 4-2). In conventional networks, UEs keep track of the access nodes whose RSRP is above a given threshold and the cell selection mechanism connects each UE with the eNB/iCS associated to the strongest DL signal. According to our model, the link quality between a user *u* and an eNB/iCS *s* can be modelled through the average SINR as

$$SINR(u,s) = \frac{P(s)\cdot\Gamma(u,s)}{I(u,s)+\sigma^2} \qquad (4.1)$$

where *P(s)* is the transmission power at s and *I(u, s)* is the aggregated interference experienced at *u* and generated by the set of nodes that operate in the same carrier of *s*. Moreover, σ^2 is the additive thermal noise power and *Γ (u, s)* is the channel gain that characterizes the radio link.

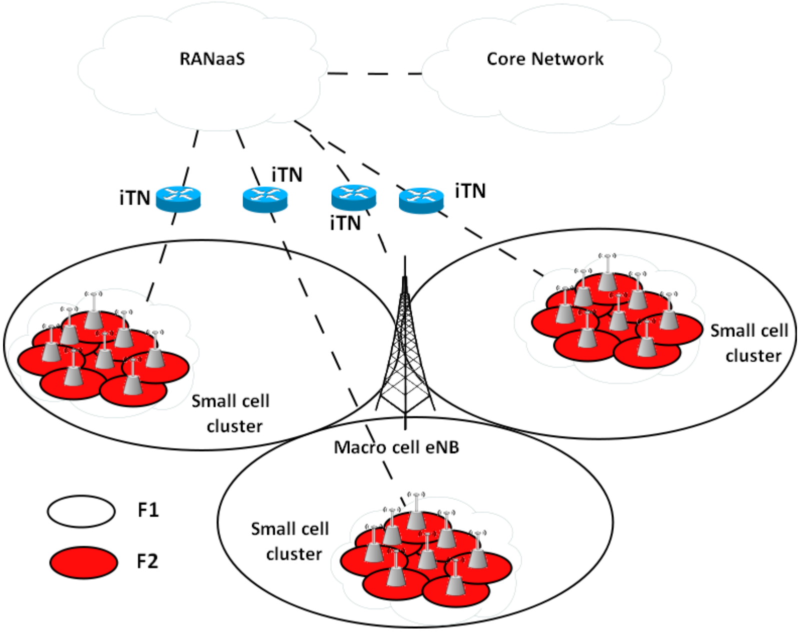


Figure 4-2: Cluster of small cells under the coverage of a macrocell.

Hence, we can denote

- The bipartite graph *G*, with vertices *U* and *S*, in which there is an edge between a user *u* and an eNB/iCS *s*, only if *u* is in the coverage area of *s* (i.e., SINR(u; s) ≥ γ_{th});
- $S(u) = \{s \in S \mid (u; s) \in G\}$, the eNBs in the active set of the user *u*;
- $U(s) = \{u \in U \mid (u; s) \in G\}$, the UEs located in the coverage area of *s*.

Although a minimum SINR is necessary at UEs to successfully decode the control channel, the SINR does not provide an intuitive description of the network performance. The data rate experienced at a given UE depends on the quality of the radio link with its serving cell; however, each eNB/iCS distributes a limited amount of radio resources to multiple users. Hence, user performance is related also to the cell load and to the scheduling policy used to allocate available resources amongst active UEs. Eventually, as previously discussed, RAN may be constrained by the backhaul capacity, especially in hot spots where service requests may be characterized by very high data rate requirements. Considering together these aspects in the cell selection process may be complex, in particular because resource allocation is carried out in faster time scale than cell association. However, analysing the network ergodic capacity can offer bounds on the overall network performance and may represent a key metric to optimize the cell selection process. To better understand these relationships, we provide here an analytical framework that models the achievable rates in heterogeneous networks in terms of cell load, backhaul constraints, and resource allocation policy. First, we can define the cell selection process as follows:

Definition: A cell selection is a mapping $\alpha: U \rightarrow S$, such that $\alpha(u) \in S(u)$, $\forall\, u \in U$.

Moreover, $\forall\, s \in S$, we define $U_\alpha(s) = \{u \in U \mid \alpha(u) = s\} \subset U(s)$, the set of users associated with s. Then, the Spectral Efficiency (SE) related to the radio link between the user u and its serving eNB/iCS $\alpha(u)$ is a logarithmic function of the SINR

$$\eta(u,\alpha(u)) = \log(1 + SINR(u,\alpha(u))) \qquad (4.2)$$

Therefore, the achievable rate at the UE u served by iSC $\alpha(u)$ can be denoted as

$$C_\alpha(u) = f \cdot B_\alpha(u) \cdot \eta(u,\alpha(u)) \qquad (4.3)$$

where $B_\alpha(u)$ is the part of the overall bandwidth B allocated to u, which depends on both the radio resource allocation policy and on the cell load at $\alpha(u)$. Moreover, f is a normalization factor, such that

$$\begin{array}{lr} f = 1, \quad if & \sum_{u' \in U_\alpha(\alpha(u))} B_\alpha(u') \cdot \eta(u',\alpha(u)) \le C^{bk}(\alpha(u)) \\ f \in (0,1), & otherwise\ (see\ below) \end{array} \qquad (4.4)$$

Eq. (4.3) and Eq. (4.4) indicate that when the DL transmissions at an iSC $\alpha(u)$ are constrained by the backhaul capacity $C^{bk}(\alpha(u))$, the iSC has to limit the usage of available radio resources, either in terms of allotted bandwidth or spectral efficiency. In this case, we must have

$$\sum_{u' \in U_\alpha(\alpha(u))} C_\alpha(u') = C^{bk}(\alpha(u)) \qquad (4.5)$$

By injecting Eq. (4.3) in Eq. (4.5), we can compute f as

$$f = \frac{C^{bk}{}_\alpha(u)}{\sum_{u' \in U_\alpha(\alpha(u))} B_\alpha(u') \cdot \eta(u',\alpha(u))} \qquad (4.6)$$

Therefore, Eq. (4.3) can be rewritten as

$$C_\alpha(u) = \begin{cases} B_\alpha(u) \cdot \eta(u,\alpha(u)), \quad if & \sum_{u' \in U_\alpha(\alpha(u))} B_\alpha(u') \cdot \eta(u',\alpha(u)) \le C^{bk}(\alpha(u)) \\ C^{bk}{}_\alpha(u) \cdot \dfrac{B_\alpha(u) \cdot \eta(u,\alpha(u))}{\sum_{u' \in U_\alpha(\alpha(u))} B_\alpha(u') \cdot \eta(u',\alpha(u))}, & otherwise \end{cases} \qquad (4.7)$$

Finally, given the definition of the user achievable data rate, we define the cell capacity as

$$C_\alpha(s) = \sum_{u \in U_\alpha(s)} C_\alpha(u) \qquad (4.8)$$

and the overall network capacity as follows as

$$C(\alpha) = \sum_{u \in U} C_\alpha(u) = \sum_{s \in S} C_\alpha(u)\,. \qquad (4.9)$$

Second study:

As stated in the state-of-art section, game theory offers an interesting perspective to deal with distributed solutions which achieve near optimum performance [118-119]. Since these distributed solutions are less intensive in terms of computational load than the calculation of the optimum cell selection scheme (which may imply solving a MINLP problem), we can use them as well to obtain an approximation to the optimal allocation in a fast and centralised way. Therefore, we model the cell selection process as a formal game and perform the algorithmic design by correctly defining the set of players and the utility functions. In the following, we use the same system model and problem formulation of the previous case.

Let be the game $\Gamma = \{P, \{S_i\}_{i\in P}, \{u_i\}_{i\in P}\}$, where *P* is the finite set of players, S_i is the set of strategies of player *i* and u_i: *S* → R is the utility function of that player (defined below), with $S = x_{i\in P} S_i$ the strategy space of the game. Players will selfishly choose the actions that improve their utility functions considering the current strategies of the other players. In our case, the players of the game represent the users that connect to the network (*P* = *U*). It is worth noting that it is not the physical users the ones that select their strategy in the game (i.e. physical users are not in charge of the cell selection process), but the network itself using a "virtual" representation of them as players of the game used to represent the cell selection process.

The set of strategies S_i of a user with *n* small cells in the set B_i is formed by the Cartesian product of the set of strategies of each link in L_u: $S_i = A_1 \times A_2 \times \dots \times A_n$. Each link represents a possible connection between a user and a small cell. Additionally, each A_j represents the set of link strategies that can be used to connect user *i* to the *j* small cell in B_i. Each link strategy $a_l = (p_l, c_l)$ is the allocation of transmission power and frequency channel for that link.

One general key issue when designing a game is the choice of u_i so that the individual actions of the players provide a good overall performance. Considering the different alternatives of utility functions, we propose the following two games to analyse the system.

Potential Game: A potential game is a game for which there exists a potential function *V*: *S* → R such that:

$$\Delta u_i = u_i(s_i, s_{-i}) - u_i(s_i', s_{-i}) = \Delta V = V(s_i, s_{-i}) - V(s_i', s_{-i}) \qquad \forall i \in P,\ \forall s_i, s_i' \in S_i$$

This definition implies that each player's individual interest is aligned with the groups' interest, since each change in the utility function of each player is directly reflected in the same change for the potential function.

If only one player acts at each time step and that player maximizes or at least improves its utility, given the most recent action of the other players, then the process will always converge to a Nash Equilibrium (NE). In addition, global maximizers of the potential function *V* are NE, although they may be just a subset of all NE of the game. These interesting properties of potential games suggest their utilization as an approximation for the optimal value of the network capacity. In this case, the utility function would be equal to the potential function and this equal to the global capacity of the network.

$$u_i(s_i, s_{-i}) = C(\alpha_i)$$

Local Game: This solution models each user as a selfish player which wants to maximize their own capacity, but adding a certain grade of cooperation to approach the global maximization objective. The utility function of player *i* is directly related to the capacity of user *i*:

$$u_i(s_i, s_{-i}) = \begin{cases} C_\alpha(u) & \text{if } C_\alpha(u) \neq 0 \text{ and } p_i > 0 \\ 0 & \text{if } p_i = 0 \\ -1 & \text{otherwise} \end{cases}$$

Therefore, the utility is the capacity of a specific user if and only if this capacity is higher than 0. The value -1 in the utility function also tries to introduce a degree of cooperation to compensate the inherent selfishness of this game: if the user cannot be connected, it is better to stop its transmission to reduce the interference on the remaining users. To ensure the existence of at least one NE and the convergence of the game to one of them, we set a threshold for the maximum number of non-consecutive times that a player can choose a specific strategy. With this simple rule, the game has a NE at least: if all the players remove the strategies that exceed their corresponding thresholds without achieving a NE, ultimately the strategy space of the game will be formed by only one possible strategy for each player, which must be a NE of the game.

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 iSCs, 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 [96].

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 the existing backhaul limitations.

In particular, cell Discontinuous Transmission (DTX) [97], which enables eNBs to switch off radio equipment in sub-frames where there are no user data transmissions, and New Carrier Type (NCT) [98], which is a 3GPP release 12 solution to reduce signalling overhead at small cells, can be combined to limit energy consumption at small cells.

In fact, a main constraint for reducing energy consumption in current cellular network standards is the requirement at eNBs to continuously broadcast system information and cell specific signals for both synchronization and channel estimation purposes. These control symbols are transmitted in each PRB and every subframe, which results in high overhead, and also limits the time where an eNB transmission function can be deactivated. With NCT, an iSC is intended to transmit solely data as well as UE-specific reference symbols, which are transmitted only in PRBs used for data. With this approach, the Radio Resource Control (RRC) protocol is fully managed by a neighbouring macro eNB. Accordingly, the C plane for UEs served by small cells is provided by the macro cell. This mechanism also increases the Spectral Efficiency at small cells, which in turns further limits the cell duty cycle and reduces energy consumption.

To evaluate the network power consumption, we use the EARTH Energy Efficiency Evaluation Framework (E^3F), which maps the radiated RF power (P_{out}) to the power supply of a base station site and underlines the relationship between the load and its power consumption. Such a study is based on the analysis of the power consumption of various LTE base station types as of 2010. The effect of the various components of the transceivers is considered: Antenna Interface, Power Amplifier (PA), the small-signal RF transceiver, baseband interface, a DC-DC power supply, cooling, and AC-DC supply. Therefore, the E^3F proposes a linear power consumption model that approximates the dependency of the power consumption on the cell load:

$$P_{in} = \begin{cases} N_{TRX} P_0 + \Delta_p P_{out}, & 0 < P_{out} \le P_{\max} \\ N_{TRX} \cdot P_{sleep}, & P_{out} = 0 \end{cases} \tag{4.10}$$

where Δ_p is the slope of the load-dependent power consumption, N_{TRX} is the number of transceiver chains, and P_{max} is the RF output power at maximum load. Moreover, P_0 and P_{sleep} indicate the power consumption at minimum non-zero load, and in sleep mode, respectively.

Table 4-7 shows the reference values of N_{TRX}, P_{max}, P_0, Δ_p, and P_{sleep} for eNBs, Remote Radio Heads (RRHs), Micro, Pico, and Femto cells, respectively.

Current systems mostly lack of sleep capabilities, however, P_{sleep} depends on the hardware components that are deactivated during sleep intervals. Furthermore, more deactivated hardware components result in a longer activation process.

Table 4-3: Base station parameters for the power model in Eq. (4.4).

Base Station Type	N_{TRX}	P_{max} [W]	P_0 [W]	Δ_p	P_{sleep} [W]
Macro	6	20	130	4.7	75
RRH	6	20	84	2.8	56
Micro	2	6.3	56	2.6	39
Pico	2	0.13	6.8	4	4.3
Femto	2	0.05	4.8	8	2.9

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

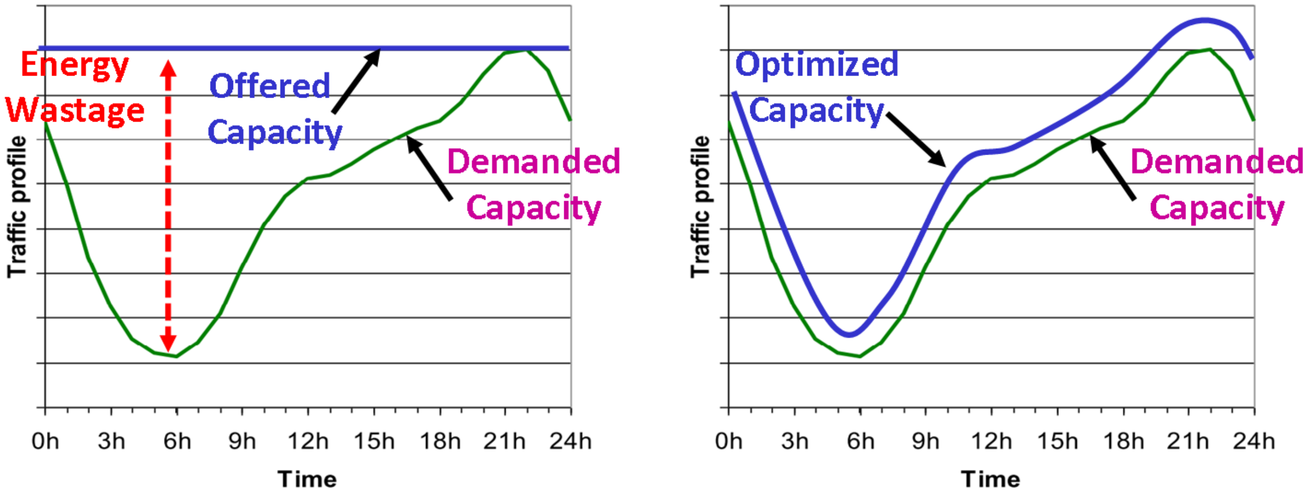


Figure 4-3: Adaptation of the offered capacity to demand to increase power efficiency.

4.3.2 Assumptions and requirements

We consider a scenario with dense small cell deployment, where the small cells are characterized by non-ideal backhaul, in terms of both latency and capacity.

iSCs are assumed to be associated to RANaaS through the J1 interface, which enable centralized management in the wireless network.

Also, J2 interface is assumed to enable direct exchange of information amongst neighbouring iSCs, and enable decentralized coordination when the centralized approach is not feasible.

Furthermore, synchronization amongst small cells and eNB is required to enable fast cell discovery; this feature is permitted through exchange of signalling on the X2 interface.

Finally, we also consider a low probability of overflow in the backhaul because of too high radio access rates.

4.3.3 Expected Outputs

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 consumed by current systems, which in turn limit the operational cost of 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 objectives.

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 to exploit centralization gains in cloud-processing considering backhaul constraints in the 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 processor, to determine the optimal schedule, and to provide the scheduling decision to the individual base stations.

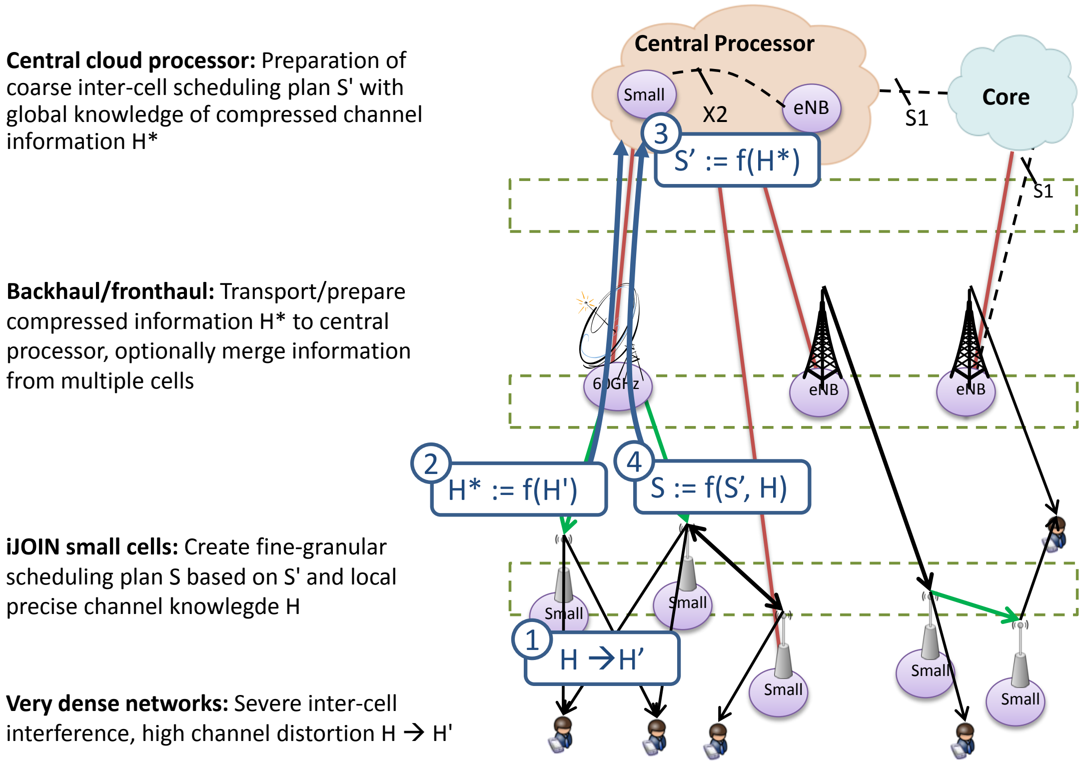
As depicted in Figure 4-4, the scheduler is divided into two stages. A coarse-grain scheduler at the central entity based on global but imperfect (quantized and outdated) channel state information, and a second stage at the iSC based on local but less quantized and outdated CSI.

The goal of this two-stage scheduling is to achieve an optimal throughput-complexity tradeoff. This trade-off measures the achievable throughput in the system and the complexity which needs to be invested in order to achieve this throughput. Usually, the higher the throughput, the higher the complexity that needs to be invested. In addition, the algorithm can be evaluated based on the actual performance-benefit gained through each invested bit of cooperation. This measure is important to evaluate whether the application of an algorithm is reasonable under a given complexity and backhaul constraint. In the course of the investigation of this two-stage scheduler, we will perform a comparison of measures with multi-cell transmission and reception algorithms (CoMP) in order to evaluate the regions of interest for both technologies. Furthermore, we are going to derive an estimate of the required computational complexity under a given set of parameters including number of users, number of cooperating cells, quality of CSI, and backhaul constraint. This estimation is important for an efficient load balancing at the central scheduler in order to exploit the available computational resources efficiently.

The basic methodology of the two-stage scheduler is to retrieve coarse-grain CSI at the central scheduler from multiple cells. Based on this information, the central scheduler derives a resource assignment for all cells where a particular resource may be occupied by more than one UE, i.e. we perform a binning where each bin (assigned to a physical resource block) may contain more than one UE. This allows for a more efficient local scheduling at the iSC which may choose out of a set of UEs which “reasonable” choices for a particular PRB.

The assignment of more than one UE to a particular PRB has a couple of advantages. Among others, if the latency between central and local scheduler is rather high, it may happen that buffers are empty or the actual throughput was lower than expected and therefore also the utility metric is changed. Hence, the local scheduler can react to these changes and schedule the UE which appears to be optimal from a local perspective. Furthermore, the central scheduler allows for efficient inter-cell interference coordination while the local scheduler can efficiently implement link adaptation and utility metric updates.

In order to make sure that this algorithm works, the coherence time of CSI feedback needs to be in the order of the latency between local and central scheduler. Coherence time of CSI feedback means the expected time in which the quantized CSI feedback remains within a certain value range. This is similar to channel coherence but the coherence time of CSI feedback is higher than the channel coherence because small changes of the channel potentially do not affect the quantized CSI and therefore would not change the result of the central scheduler. Therefore, the higher the backhaul latency is, the more coarse-grain the CSI feedback is. After the local scheduler performed the local resource assignment, it will send an update to the central scheduler including update CSI as well as update utility metrics.



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.

With the introduction of this two-stage scheduler, also challenges need to be addressed. Among others, the local updates of the utility function need to incorporated at the central scheduler. However, these updates may be quantized as well as because of the changes between feeding back this update and performing a new resource assignment. Furthermore, the utility metrics need to be adjusted, e.g. the PF metric should be aware of the channel uncertainty and the corresponding uncertainty about the correctness of the PF metric. The new metric will perform between the actual PF metric for perfect CSI and the fair scheduler (if no CSI is available). Furthermore, the number of UEs per bin needs to be optimized in order to minimize the exchange of information between central and local scheduler but to guarantee being as close as possible to the optimal system performance. Finally, the actual scheduling needs to take the coherence time and bandwidth of the individual UEs into account in order to maximize the probability that each bin contains the optimal scheduling choice.

4.4.2 Assumptions and Requirements

This CT will require information about the following parameters:

- Signal-strength per UE and assigned eNB
- Interference-strength at each eNB
- Information about the backhaul parameters such as latency and load (in general, BH state information)
- Coherence time/bandwidth for individual UEs based on speed and channel estimation

The CT will make use of the J1 in order to flexibly distribute the resource assignments among the individual iSCs. This CT fits well into the concept of the veNB by implementing one central scheduler for each veNB deciding upon the scheduling decision for all iSCs managed by this veNB.

4.4.3 Expected Outputs

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 iSCs, 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.

iSCs 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 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 cells to enable a reliable estimation of the co-channel interference with a limited overhead.

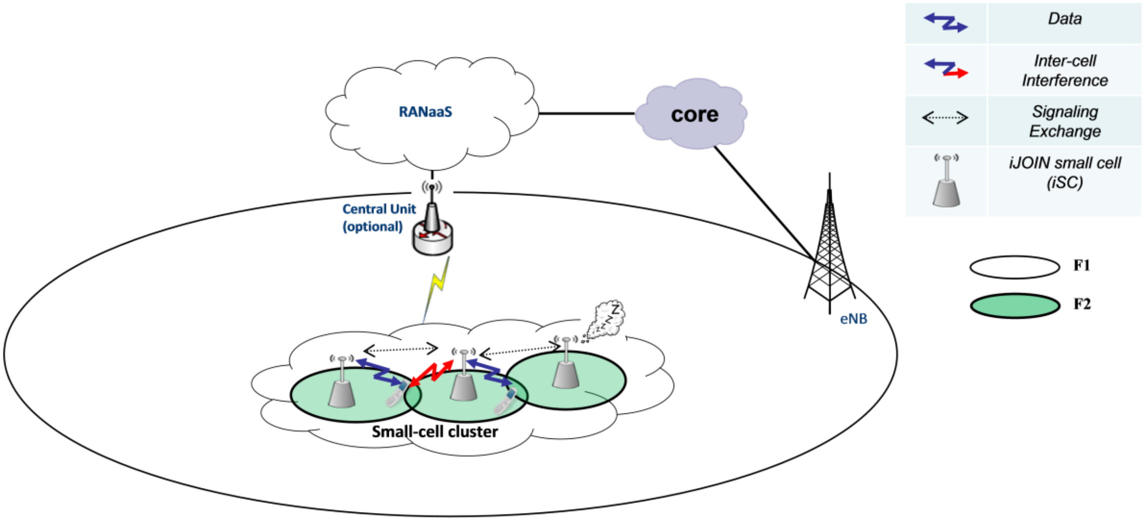


Figure 4-5: Inter-cell interference coordination between iSC.

4.5.2 System model and problem formulation

Here, the system is considered as a downlink multi-cell OFDMA cellular network that consists of a dense deployment of small cells. Each small cell is served by a single, randomly located, antenna denoted as iSC. The entire network is regarded either way as an enterprise or domestic environment that comprises L s-APs. Each iSC serves M_l users and the total number of users in the system is the aggregation of the users of all L iSCs, such that $M_t = \sum_{l=1}^{L} M_l$. Here, $m(l) \in M_l$ represents the user attached to iSC l, for $L = \{l \mid \forall l \in 1, 2, ...,L\}$ assuming each user is served by only one s-AP. This system also includes a local entity that acts as the control unit that resolves the conflicts (in terms of interference) in the small cell network.

In the small cell network, the problem of network optimization can be translated to a weighted sum rate maximization problem where the weighting factors can be tuned accordingly to maintain fairness or other per user service requirements of the network. Let $w_{m,n}, m \in M_t, n \in N$ be arbitrary user weights taking into account instantaneous QoS requirements and $R_{m(l),n}$ the achievable user's data rate in terms of spectral efficiency on each sub-channel (using the truncated Shannon capacity formula) and is represented as: $R_{m(l),n} = \log_2(1+\rho \cdot SINR_{m(l),n})$ where ρ accounts for the SNR gap observed in practice in a system using adaptive modulation and coding for a given Bit Error Rate (BER) ($\rho = -1.5/\ln(5 \cdot BER)$). The corresponding SINR is: $SINR_{m(l),n} = P_{l,n} G_{m(l),l,n} / \sum_{i \neq l \in I_{m(l),n}} P_{i,n} G_{m(l),i,n} + \eta$.

Here, $P_{l,n}$ is the small cell transmit power and $G_{m(l),l,n}$ is the channel gain between iSC l and UE m in the sub-channel n. Moreover, η is the power of the thermal noise and $I_{m(l),n}$ accounts for the set of the interferers in a specific sub-channel n. The optimization problem here is to find the optimal resource allocation (subcarrier and power control) in order to maximize the weighted sum-rate:

$$\max_{A,P_{l,n}} \sum_{l=1}^{L} \sum_{m(l)=1}^{M_l} \sum_{n=1}^{N} w_{m(l),n} R_{m(l),n} a_{m(l),n} \tag{4.11}$$

Subject to:

$$a_{m(l),n} \in \{0,1\}, \forall\, l \in L, n \in N, \tag{4.12}$$

$$\sum_{n=1}^{N} P_{l,n} \leq P_{l,\max}, \sum_{n=1}^{N} P_{l,n} \leq P_{l,max} \tag{4.13}$$

$$\sum_{m(l) \in M_l} a_{m(l),n} \leq 1, \forall\, l \in L, n \in N \tag{4.14}$$

where $A = \{a_{m(l),n} \mid a_{m(l),n} \in \{0,1\}\}$is the binary variable corresponding to the allocation decision for the sub-channel *n* to user *m* of s-AP *l*, *i.e.* $a_{m(l),n} = 1$ if user *m(l)* is allocated sub-channel, where $N = \{n \mid \forall\, n \in 1, 2, \ldots, N\}$ is the set of sub-channels. Moreover, $P_{l,n}$ accounts for the s-AP transmit power per sub-channel. Hence, the optimization problem is weighted sum-rate maximization over the network in presence of inter-cell interference subject to power constraint of $P_{l,\max}$ per node *l* as in Eq. (4.7) and orthogonal allocation at intra-cell as in Eq. (4.8).

Proposed Graph-based Framework:

The generic weighted rate maximization problem as described in Eq. (4.5) is a non-convex optimization problem with non-linear constraints and was shown to be NP-hard. In this work we investigate a holistic graph-based solution that targets improving the per UE service while maintaining the level of spectral efficiency via better dynamic reuse across the cells in a networked small-cell environment. This involves a locally-centralized graph-based Inter-cell Interference Coordination (ICIC) via user partitioning across different clusters. Subsequently, the resource allocation policy is formulated as weighted sum rate maximization (WSRM) to optimize system performance in terms of both throughput and fairness.

Inter-cell interference is managed through an adaptive graph-based ICIC scheme which combines graph-partitioning and local search concepts to provide near-optimal interference isolation between users of different cells. Subsequently, the adaptive clustering of users based on their mutual interference levels results into an SNR maximization problem where optimal resource allocation is accommodated by a central coordinator (i.e. the RANaaS entity) for clusters of users aggregately.

- **Graph-Construction:** An interference graph *G (V, E)* is created, that consists of *V* vertices that correspond to the users in the system and *E* edges that show the downlink interference conditions between users. An edge between them logically shows the level of signal degradation to both users assuming they utilize the same resource part. This graph is a weighted un-directed graph that connects all the users in the system. This interference graph is constructed in the RANaaS entity. For the graph construction, we use a metric corresponding to the relative channel qualities for each pair of users. This metric encapsulates channel statistics to represent the worst case interference that each pair of users can experience at a specific sub-channel (path loss, shadowing effect and fading).
- **Graph-partitioning:** Having formed the interference graph, we then focus on the graph-partitioning phase, proposing a novel formulation for the efficient partitioning of users into clusters. The WSRM

problem can be mapped into the problem of optimal partitioning of users into each cluster via employing the already created weighted interference graph. Such partitioning can be decomposed into a set of graph-based sub-problems, termed as Minimum Path Selection (MPS) per sub-channel. Each MPS sub-problem solution comprises a path of a certain size $l=1,2,..,L$. In other words, the original WSRM problem will be decomposed into finding the maximum weighted sum-rate out of $L-1$ MPS sub-problems per sub-channel. It will be proven that MPS is an NP-hard combinatorial optimization problem as it is a close match to the well-known problem of Exact Generalized Traveling Salesman Problem (E-GTSP). As a result, we propose heuristic algorithms to efficiently solve it in an efficient way.

4.5.3 Assumptions and requirements

iSCs are assumed to be associated to a locally deployed controller (RANaaS entity) which manages a cluster of iSCs and connect the iSCs to the core network. The J2 interface is assumed to enable exchange of information in a cluster of iSCs and J1 between iSCs and RANaaS.

4.5.4 Preliminary Results

Due to NP-hardness of the MPS sub-problem, it is crucial to seek heuristic solutions to address the problem in an efficient manner. Therefore, we propose such a solution comprising three key steps:

- Selection of Representatives: This step enables the selection of one representative node corresponding to each cell. This representative node is the user with the best experienced signal quality towards his serving small cell.
- Generation of multiple minimum-cost paths for each representative: Thereafter, from each representative, the minimum-cost paths are calculated. The minimum cost path is calculated by taking the intra-path sum weight, i.e. the sum of all the edges' weight combinations for the nodes composing the path. Note here that the minimum cost paths that are generated can be sub-optimum solutions due to falling in local optima. In this stage, we generate a population of feasible solutions with path size l. The same procedure is repeated for all the representatives. As duplicate paths might be generated in this process, those are to be excluded from the feasible solution set at the end of this step.
- Selection of Minimum path: In this step, from the set of feasible solutions generated in the previous step, we select the minimum path of size l as the path with the lowest intra-path sum-weight among them.

Following, considering $\forall\, l \in L$ as a variable for which MPS sub-problem is applicable, we can obtain $L-1$ minimum paths in the aforementioned graph consisting of $V_1,V_2,...,V_L$ disjoint subsets. Therefore, the problem of the optimal partitioning of users into a cluster can be seen as finding the optimal $\forall\, l \in L$ for which the Weighted Sum Rate (WSR) of the users comprising the minimum path is maximized. This problem is performed for all sub-channels independently (N times), resulting in N clusters of users in which the WSR gets maximized. One challenge here is that due to different levels of reuse factor in outcome solution per sub-channel, it is not possible to determine in advance the power level per resource and it can mutually affect the resource allocation scheme. The aforementioned challenge requires an iterative power allocation algorithm on top of the graph-partitioning based channel assignment. Here, we apply the optimum power allocation as derived in [99]. This algorithm is an iterative power allocation scheme dealing with the problem described above. The concept in this algorithm is to iteratively adjust the power-level per resource for each iSC based on the cluster channel assignments since the number of used resources per iSC is unknown in advance.

The system consists of a dense iSC deployment and a local controller (i.e. RANaaS). The small-cell deployment used in this study is a 3x3 grid of apartments. In this deployment, each iSC and 4 users are randomly distributed in each apartment. The 5x5 path loss model is used to evaluate our model in a dense deployment of small cells derived from 3GPP [9]. For evaluation purposes our proposal is compared with the case where interference management is only available via Intra-cell Scheduling (Proportional Fairness) in Reuse-1 scenario. Furthermore, we compare our proposal towards competitive graph-based Dynamic ICIC approaches that were introduced in [100]-[102]. The following figures show the gains of our proposal taking the CDF of user spectral efficiency (Figure 4-6-left) and the CDF of cell spectral efficiency throughput (Figure 4-6-right) as a performance metric for the achievable per cell spectral efficiency.

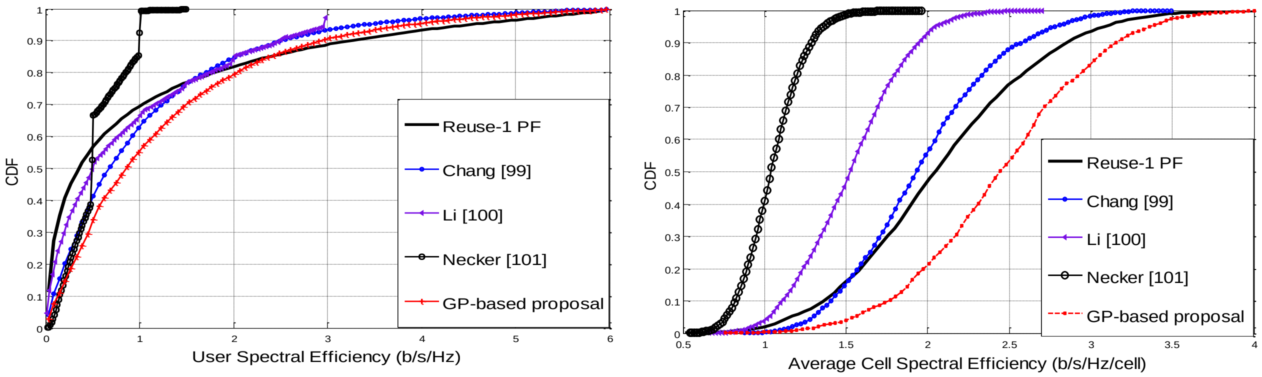


Figure 4-6 CDF of user spectral efficiency (left) and CDF of cell spectral efficiency (right).

4.6 CT 3.6: Assess and Increase Utilization and Energy Efficiency

4.6.1 Scenario Description

Measurements in operator networks reveal [103] that 20% of all base stations carry 50% of the overall traffic, meaning that the average utilization ratio is less than 40%. The main reason for this phenomenon is a wide deployment of macro-cells to achieve a high coverage, and the network dimensioning trimmed to peak traffic demands, meaning that a large fraction of deployed resources are underutilized. iJOIN aims at increasing this utilization efficiency up to 75% by means of its two technology pillars (RANaaS decentralization and joint RAN/backhaul design).

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 the other two efficiency objectives of iJOIN, which are *cost* and *energy* efficiency.

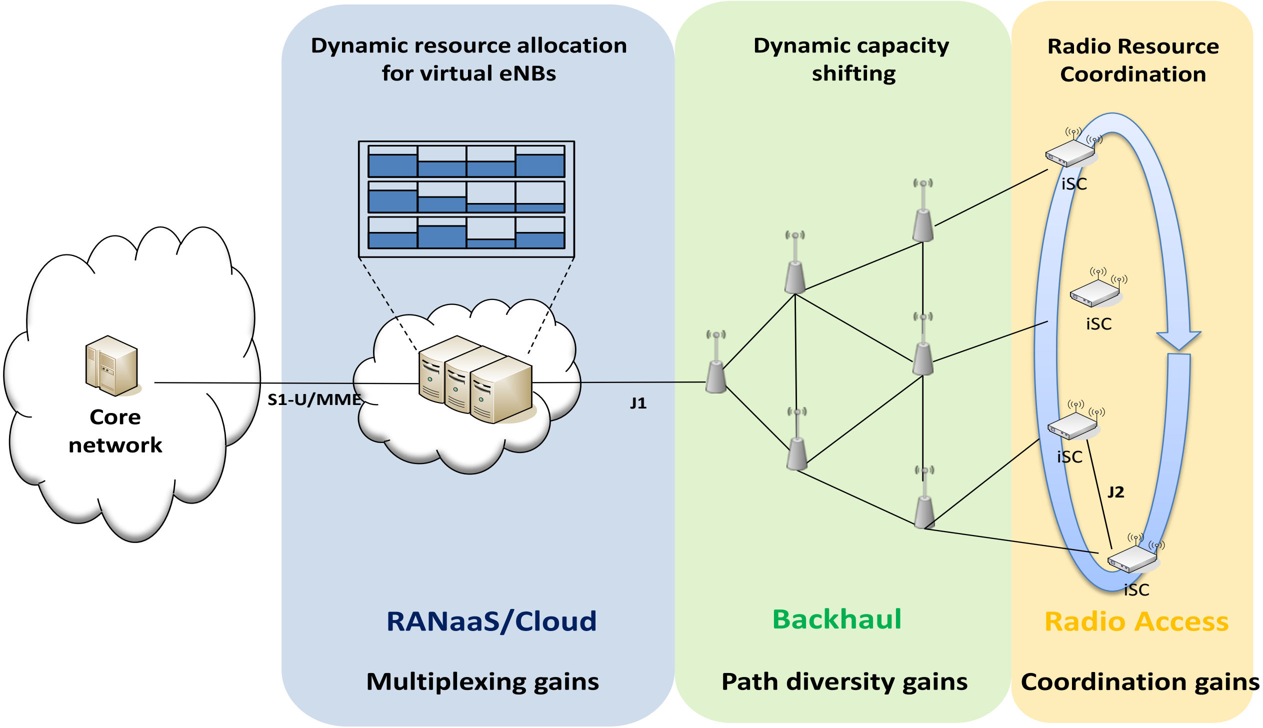


Figure 4-7: Resource allocation techniques in different iJOIN domains and their expected gains.

Figure 4-7 shows an example of 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 the 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; adaptation gains in the backhaul due to flexible shifting of link capacities according to the traffic demands; dynamic backhaul routing in case of a mesh layer availability.

The performance analysis will be based on appropriate abstractions of different technology candidates proposed in iJOIN. It will also investigate the relationship between certain performance constraints (Key Performance Indicators, KPIs) and the related limits of the achievable utilization efficiency. The relevant KPIs could be for instance overall spatial coverage, minimum guaranteed bandwidth, call drop likelihood, cell interference, etc.

An initial snapshot of resource/network mapping is shown in Table 4-4.

Table 4-4: Preliminary mapping of resource types to network entities

Resource type \ network entities	Radio access	Fronthaul	Backhaul	RANaaS
Radio resources[1]	e.g. PRBs	if applicable	if applicable	N.A.
Bandwidth	e.g. cell capacity	e.g. link capacity	e.g. link capacity	N.A.
Hardware/ computational resources	e.g. hardware elements	N.A.	N.A.	e.g. CPUs

Utilization metrics can be defined at each individual domain, as well at a holistic system level. Typical known metrics in the individual domains are reported in Table 4-5.

Table 4-5: Examples of partial utilization metrics

Radio access	*Radio Resource Utilization (RRU)*. In LTE, one common metric is the number of occupied Physical Resource Blocks (PRBs) compared to the total available PRBs
	Baseband Hardware Resource Utilization (BHRU): common base station architectures comprise Hardware Elements (HEs) for baseband processing. The BHRU can be defined as the number of occupied HE compared to the total number of available HE.
Backhaul	*Bandwidth Utilization (BU):* The total throughput compared to the capacity of a backhaul link
RANaaS	*Datacenter capacity utilization*: sum of the CPU usage values for all the servers in a datacenter.

In iJOIN, utilization efficiency metrics relate a given resource usage to a specific KPI. For example, if the cell throughput is the chosen key performance indicator, the Radio Utilization Efficiency (RUE) can be expressed as the throughput divided by Radio Resource Utilization (RRU):

$$\mathrm{RUE} = \mathrm{throughput}/\mathrm{RRU} \quad (4.10)$$

Utilization and utilization efficiency metrics which consider the whole iJOIN architecture are subject to on-going research in WP3.

Energy efficiency is defined as a qualitative metric expressing the impact on power (or energy) consumption of the transition from the standard 3GPP eNB architecture to the iJOIN model. In general, the full scenario needs to be evaluated to make fair comparisons:

- The energy spent in the iJOIN small cells for the computational part (excluding radio functions);
- The energy spent inside the cloud for the servers in the datacenter hosting the computation related to the RANaaS decentralized processing functions;

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[1] Only for transmission technologies allowing flexible resource allocation (e.g. TDMA)

- The energy necessarily spent as “due overhead” inside the cloud datacenter, i.e. the air conditioning, the Uninterruptible Power Supply (UPS) and other facility related consuming equipments (lights, etc);
- The energy spent in the backhaul links (logically separated by the iSCs for this specific metric).

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. The PUE is commonly defined in the following way:

$$\mathrm{PUE} = (\text{Total Power Consumption}) / (\text{ICT Equipment Consumption}) \quad (4.11)$$

Energy efficient datacentres have PUE < 1.5; an average PUE value is around2, while PUE > 3 denotes a datacenter with very bad energy efficiency.

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

- the sum of the power for the cells with eNBs in the standard 3GPP architecture (P_{eNB});
- the sum of all power for the small cells (1) (P_{iSC}), plus the power of the servers (2) times the PUE of the datacenter (P_{CL}), plus the power of backhaul links (4) (P_{BH}) (Figure 4-9).

So, referring to Figure 4-8, a general expression of global energy efficiency can be:

$$\mathrm{Eff}_{\mathrm{E}} = (\mathrm{P}_{\mathrm{iSC}} + \mathrm{P}_{\mathrm{CL}} + \mathrm{P}_{\mathrm{BH}}) / \mathrm{P}_{\mathrm{eNB}} = \mathrm{P}_{\mathrm{iJOIN}} / \mathrm{P}_{\mathrm{eNB}} \quad (4.12)$$

Such expression might (in general) be greater than 1, meaning that the energy efficiency of iJOIN is worse than the one of a legacy LTE eNodeB. This is because introducing the RANaaS also brings into the system extra power consumption due to the physical cloud infrastructure implementing the RANaaS itself. Clearly, the goal of iJOIN is to prevent this from happening, and many candidate technologies are intrinsically designed to achieve power optimizations. Nevertheless, it can be possible that in some scenarios a trade-off is accepted, increasing the energy usage in return of other advantages (scalability, speed of deployment,…). Should such cases appear, it will be important to carefully assess the amount of induced additional power consumption. In the long term, function decentralization should take advantage of the outcomes from other research paths, for instance the projects targeting increase of renewable energy usage for supplying datacentres. These will allow to mitigate the impact of energy consumption of datacentres, so improving the energy efficiency premium of iJOIN functional split.

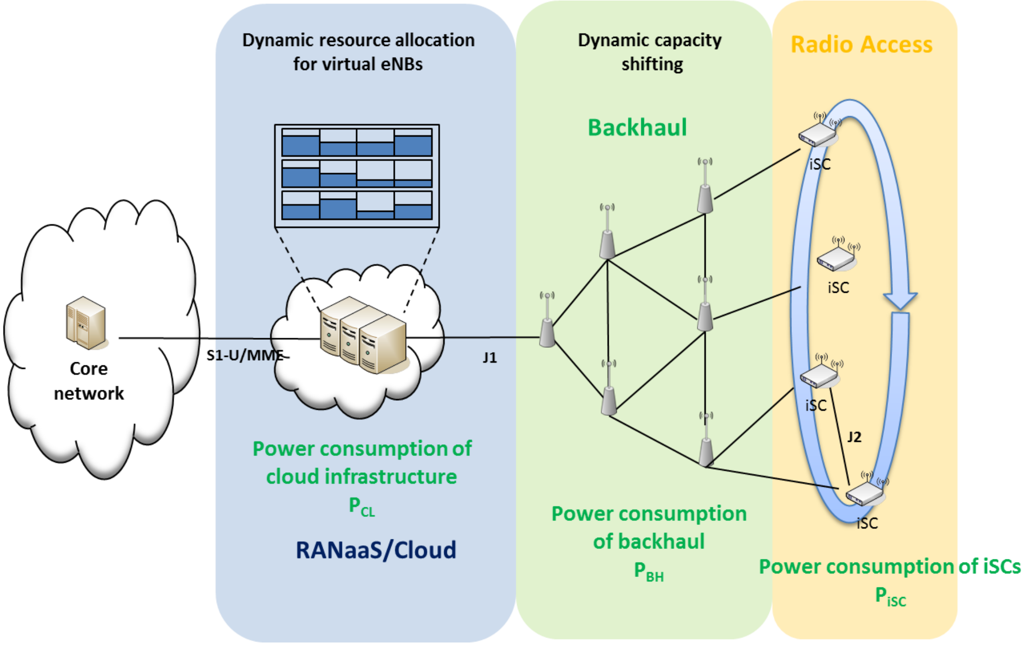

Figure 4-8 - Energy efficiency factors.

iJOIN will also investigate how a global net energy efficiency improvement can be achieved with the proposed architecture. A key enabler to investigate is the chance to break the always-on paradigm: i.e, understanding if the optimized utilization model made possible by iJOIN may allow to dynamically turning off some network and/or RANaaS gear when there is no traffic needing to use it.

In general, reducing the size of the cells and shortening the communication distance enables achieving higher data rates with lower transmitted power than conventional cells. This leads to better power-efficiency in bits/Joule, i.e. the relative energy-consumption per transmitted/received bit decreases even though the overall energy-consumption may increase due to the densification of the network. On the other hand, smaller cells provide finer spatial granularity. Therefore, better energy management is possible by turning off under-loaded cells.

Furthermore, a RANaaS based architecture paves the way to more computational energy saving in the radio access layer, at the price of an additional consumption in the datacenter.

All these factors contribute to energy efficiency that is intended to be achieved by iJOIN. Given an increase of system throughput by a factor of 100, iJOIN sets a goal to reduce energy-per-bit to less than 5% of that of current systems taking the backhaul and iSCs energy consumption into account. By applying novel architecture, approaches, and algorithms in iJOIN, this objective can be achieved by reducing:

- Transmission of energy through smaller cells and shorter distances between small cells and terminals (down to 10-20% through up to 10dB lower transmitted power, while preserving the same SINR in the interference-limited regime);
- Average per-site energy by deploying small-cells (down to 25-50%);
- Signal processing and computation energy by exploitation of diversity effects within RANaaS (down to 40-50%);
- Network energy by jointly shutting down radio access and backhaul network nodes (down by 20-50%);
- Network energy by selectively and temporarily shutting down nodes or links when they don’t need to be used (e.g., stopping broadcasting channel state information over J1 links in timeframes when decentralized interference control is not applied, or entering into the network node sleeping mode proposed by CT4.2).

The main actual metric used in iJOIN to evaluate energy efficiency should be the *amount of consumed energy per information bit* (or, the other way around, the *amount of processed information per unit of energy*), which has been also successfully used in other projects like EARTH. **Energy Efficiency** is thereby measured as an **Energy Consumption Index** defined as:

$$\eta_{\mathrm{energy}} = \frac{\text{energy consumed}}{\text{information delivered}} = \frac{\text{power consumption}}{\text{delivered data rate}} \qquad [\text{Joule/bit}] = [\text{Watt/bps}] \quad (4.13)$$

This metric normalizes the power consumed for information transmission by the actual information transmitted. It thereby decouples the energy consumption from the amount of delivered traffic. This is necessary because a higher traffic demand or larger network might require a higher total power consumption, which does not mean it cannot be more efficient than a smaller one.

The metric can be used for varying scenarios, as the following examples illustrate:

- **Link Level Example**: A backhaul link transmits 10 Gbps. All involved components (transmitter, receiver, power amplifiers, data processing ...) consume 1 kW during a sustained (full buffer) transmission. This results in an energy efficiency of 10 kW /10 Gbps = 1 µJ/bit.
- **Network Level Example**: A heterogeneous network can serve 100 users with a downlink data rate of 1 Mbps each. The power consumption of all involved components (small and macro cells, backhaul links, RANaaS) sums up to 10 MW. This results in an energy efficiency of 10 MW / (100 * 1 Mbps) = 0.1 J/bit.

It should be noted that as the information goes to zero, the metric goes to infinity, indicating an infinitely bad efficiency. This is important because a system usually consumes energy when it is not transmitting any information. This problem can be avoided by using time averaged values or assuming full buffer traffic.

Furthermore, the metric can depend on a number of other parameters, which have to be accounted in order to be able to compare two setups:

- Traffic demand or number of users;
- Utilization or load of the network/link;
- Number, deployment density and type of base stations;
- Covered area;
- Required QoS for user (e.g. minimum data rate) ;
- Uplink and/or downlink observed;
- Set of appliances considered (cells, RANaaS, network switches, transceivers, data processing devices)

If two different setups have to be compared, two other metrics can be used depending on the context:

1. Power consumption per covered area

$$\eta_{\text{energy}} = \frac{\text{power consumption}}{\text{area covered}} \qquad [\text{Watt/km}^2] \quad (4.14)$$

This metric is for example useful to compare networks of different sizes or deployment densities.

2. Power consumption per satisfied users

$$\eta_{\text{energy}} = \frac{\text{power consumed}}{\text{number of (satisfied) users served}} \qquad [\text{Watt/user}] \quad (4.15)$$

This metric is useful because it includes QoS constraints and thereby ensures a certain degree of fairness. It also offers good insight for operators as to how efficient their network is compared to how many customers they can satisfy.

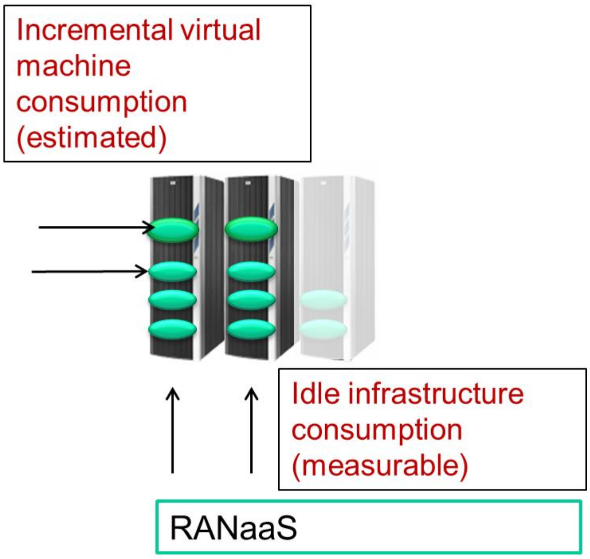

Figure 4-9 - Power measurement model in RANaaS.

Whatever metric is defined, it is key to clearly define the scenarios where the metric itself is evaluated, and to perform the comparisons with the pre-iJOIN status. In particular, it’s important to specify which candidate technologies (individual or combined) are included in any of the scenarios, since a unique iJOIN scenario, encompassing all the candidate technologies, is not planned, and the conditions of the efficiency evaluation need to be fully comparable for all the cases under evaluation.

In the IT domain, which is relevant to the RANaaS side, currently recognized metrics focus (as aforementioned) on the assessment of power consumption overhead induced by the presence of cooling and electrical facilities needed to enable the operation of a datacenter. PUE (previously defined) is the most used metric. Metrics linking the amount of “productive” work to the related energy consumption are not common yet. Some new research projects are starting to deal with this topic, but they’re just at the beginning. The main open issue is to define the right KPI to assess the unit of “product”.

4.6.2 Measurement

It must be well defined how to measure (or estimate when measuring is too complex) the power consumption for a given scenario. For the RANaaS side, power consumption can be split into two components:

- Static consumption, i.e. the power consumed by every physical node (basically a server) turned on and not executing any application related workload (idle state); this is easily measurable;
- Dynamic consumption, i.e. the additional power consumption induced on a server when a piece of computational workload is executed. In the iJOIN RANaaS environment, this turns into measuring the power consumption generated by the activation of a virtual machine (or the power decrease due to its termination). The FIT4Green research project [2] provided results to this topic, by deriving formulas where the marginal power of a virtual machine is correlated to its usage of the server's physical resources. Details are available in the deliverable D3.2, downloadable by the project website. These models will be used in iJOIN to properly evaluate the power consumption introduced by the RANaaS layer.

4.6.3 Assumptions and requirements

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.

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

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 (MPTD) principle applied in the uplink is to increase the (aggregated) throughput by improving the detection quality of the users' data or to for a given performance quality decrease the transmit power needed by the device to reach for a given performance. 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 [104]. This principle, derived from the turbo code [105], has been straightforward extended to the single-user spatial dimension (MIMO) and to the multi-user context [106] and reference herein. However, 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 implementation of the turbo detection of data related to users attached to a small cell and/or attached to different small cells (hence multi point). However, such approach clearly needs the links 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 still be able to carry all resources needed for a centralised radio resource management (RRM) enabling the turbo detection to be applied at each small cell level (hence scalable) on a reduced set of users.

In both cases, it is envisaged that the centralised RRM algorithm running in the RANaaS platform will provide on an iSC demand basis, the set of iSCs and UEs to be involved in an MPTD process, thus giving a "**long-term**" scheduling framework for each involved iSC. The "**short-term**" scheduling will take place normally at the iSC level but under this framework.

The goal of this study will be to identify the information needed for such centralised RRM algorithm to be performed in the RANaaS platform as well as the long term-scheduling framework content. In this scenario, all iSCs are connected to the RANaaS platform through a J1 link to receive long term scheduling framework if necessary. The link characteristics (capacity/latency/availability) to support such transfer between iSC and RANaaS for the centralised RRM will be investigated.

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[2] http://www.fit4green.eu

In addition, if those characteristics are sufficient, the physical turbo processing (described in detail in D2.1 [27]) could also be deported in the RANaaS platform (MPTD case in D2.1). For instance, this can be possible if the latency of the J1 link is below the millisecond, while its capacity is greater than 720Mbps when the functional split is performed after the FFT for a 20MHz LTE system with 2 receive antennas (assuming 10bits per I or Q sample).

If these requirements are not met, the turbo processing could be performed locally in each iSC identified by the RANaaS centralised RRM algorithm (SPTD case in D2.1). 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 based on the characteristic of the link. If J2 links are used, they will most likely be assumed to be very low latency link (<4ms).

To evaluate the performance, an indoor small cell deployment will be considered as shown in Figure 4-10, where possible functional split between the RANaaS platform and the flexible iSCs is highlighted (to be refined after further investigations). This split will be based on the J1 interface quality (High Quality, Medium Quality, Low Quality related to the bandwidth/latency capability of the link), while in case of local processing, the J2 interface might also be used for cooperation purpose.

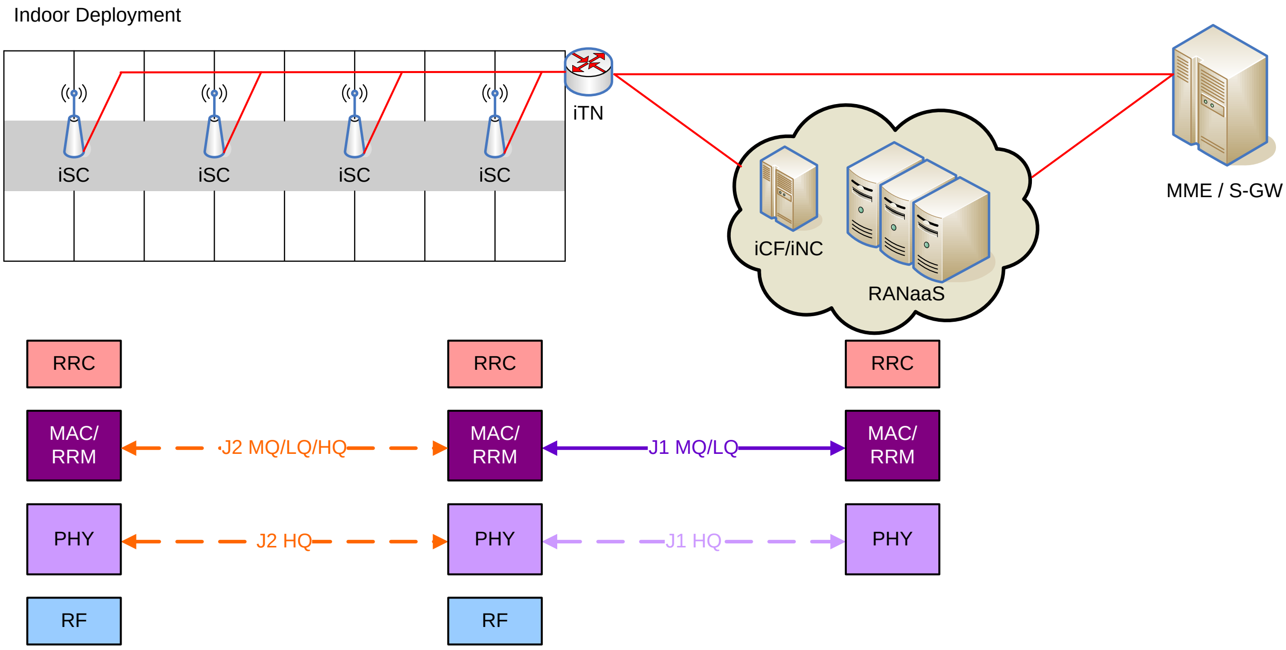

Figure 4-10: Scalable multi-point turbo detection investigation context.

4.7.2 Assumptions and requirements

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 based on the small cell backhaul capability: raw I/Q information after the iFFT, measurement/control information, resource allocation mapping…

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).

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 RRM, the 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.

The J2 interface may be exploited as well. It should be very-low latency, while its bandwidth will be a parameter.

4.7.3 Expected Outputs

This candidate technology addresses the iJOIN objective: **area throughput**, which should be increased by improving 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 characteristics. Other metrics may be improved with for instance the energy consumption of the devices (less error meaning less retransmission attempts and/or less transmit power needed for a given quality).

To evaluate the performance, Monte-Carlo based system level simulations will be performed. The Indoor Hotpot (InH) model from the ITU-R M2135 report [111] will be used at 2.6 GHz (instead of 3.5 GHz) and extended to represent a dense small cell deployment with four iSCs deployed (instead of two) as shown in Figure 4-11.

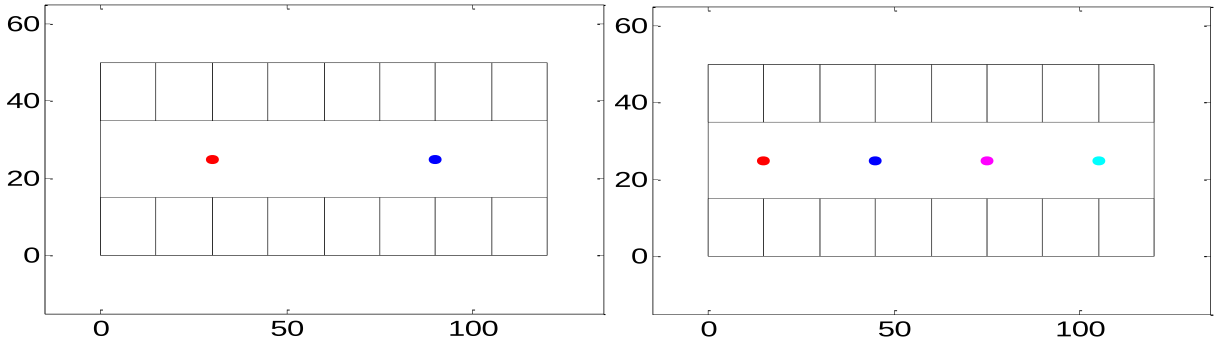

Figure 4-11: Classical (2 iSCs) and Extended (4 iSCs) InH Model (axis in meters).

Table 4-6 summarises the main parameters of the system-level simulations.

Table 4-6: System-Level Simulation Main Parameters

LTE Parameters		
Bandwidth		10MHz
Frequency		$f_c = 2.6\text{GHz}$
InH Parameters		
Block	Number	2 Rows of 8 Blocks
	Size	15m x 15m
Hall Size		20m x 120m
iSC Parameters		
Antenna	Number	2
	Pattern	Omnidirectional
	Gain	0dBi
	Height	6m
Transmit Power		21dBm
Noise Figure		5dB

UE Parameters		
Antenna	Number	1
	Pattern	Omnidirectional
	Gain	0dBi
	Height	1.5m
Maximum Transmit Power		21dBm
Noise Figure		7dB
Propagation Parameters		
Line of Sight Probability (d being the iSC-UE 2D-distance in meters)		$P_{LoS} = \begin{cases} 1, & d \le 18 \\ e^{-\frac{d-18}{27}} & 18 < d < 37 \\ 0.5 & 37 \le d \end{cases}$
Pathloss	LoS	$PL = 16.9\log_{10}(d) + 32.8 + 20\log_{10}(f_c)$
	NLos	$PL = 43.3\log_{10}(d) + 11.5 + 20\log_{10}(f_c)$
Shadowing Std Dev	LoS	$\sigma = 3\text{dB}$
	NLos	$\sigma = 4\text{dB}$

Per run, UEs will be dropped uniformly in the building and attached based on the best received power criteria as shown the drop example given Figure 4-12.

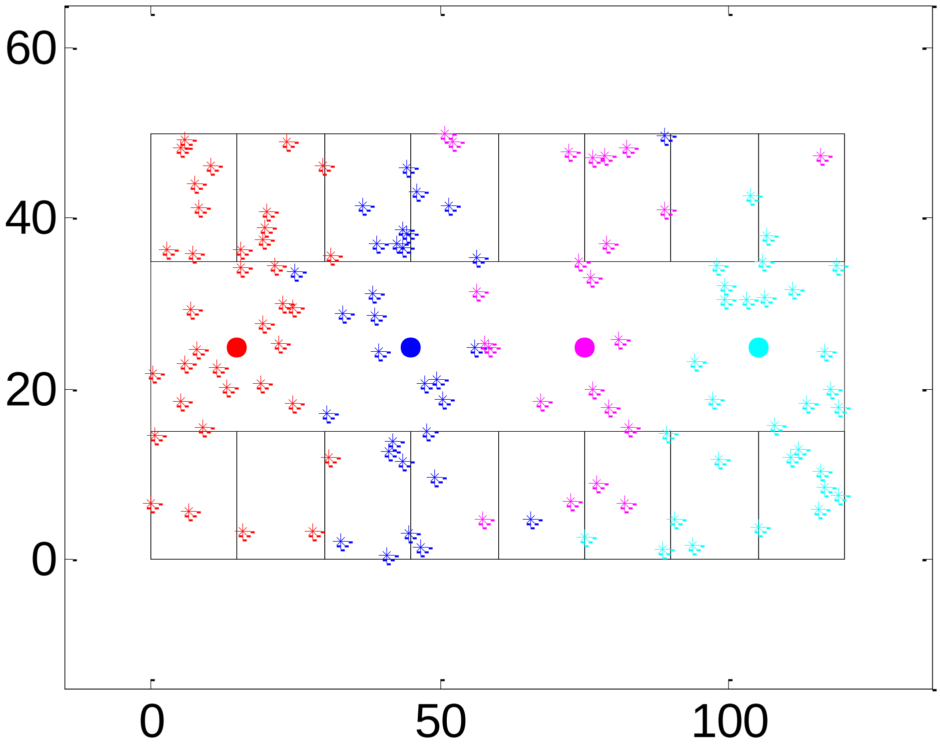

Figure 4-12: Drop Example: 4 iSCs (dot), 120 UEs (star)

4.8 CT 3.8: Radio Resource Management for In-Network-Processing

4.8.1 Scenario Description

In-Network-Processing (INP) is a technique that allows for the distributed, joint calculation of functions within a network of processing nodes. INP has been proposed for the joint detection of a message broadcasted to several receiving station, in particular in the context of wireless sensor networks [109],[110]. Consensus-based INP algorithms iteratively find an agreement on an estimate of the transmitted message. This is facilitated through the exchange of messages between the processing nodes.

In the application of dense, heterogeneous mobile networks, this approach allows for the joint detection of UE signals through several iSCs. An example scenario is depicted in Figure 4-13 where two users are associated to two different iSCs, operating on the same physical resources blocks (PRBs). In order to combat interference between the two UEs, the iSCs cooperate in order to perform a Multi User Detection (MUD) of the 2 UE signals. Two further iSCs not having users allocated on the PRBs in question can contribute to the MUD by providing their receive signals to the joint detection process.

The actual estimation algorithm and the nature of the information exchanged between iSCs in order to converge to a joint estimate are in the scope of WP2 CT2.1 [27].

The purpose of this CT is to provide RRM information and rules for cooperation for the INP algorithms developed in CT2.1. The RRM needs to be aware that a cross-iSC joint detection of UEs is taking place, and a network function is required that monitors the receive quality of a UE at different iSCs and decides which iSC should take part in the joint detection.

INP algorithms are able to find a consensus on the estimated variable as long as the network graph is connected. However, the degree of connectivity affects the speed of convergence. In a system setup where it is possible to set up J2 between iSCs dynamically, an entity is required that decides whether to establish a link or not, based on instantaneous information on the current load of the physical backhaul links carrying the J2 traffic.

Since complete orthogonality of users can barely be achieved in a heavy loaded, dense scenario, the RRM has to reuse resource elements. While a RRM not aware of the ability of joint processing by several iSCs will follow the objective of minimizing mutual interference. If several iSCs cooperate, all interference between the users of the iSC can be eliminated. With INP detection at the iSC, the RRM's task is to decide which iSCs should cooperate and then allocate users on the same resources on these iSCs. If further iSCs are available that have a J2 connection with available bandwidth, these can be added to the cooperating iSC cluster for assistance. So a joint RRM and Cell (iSC) Selection mechanism is required.

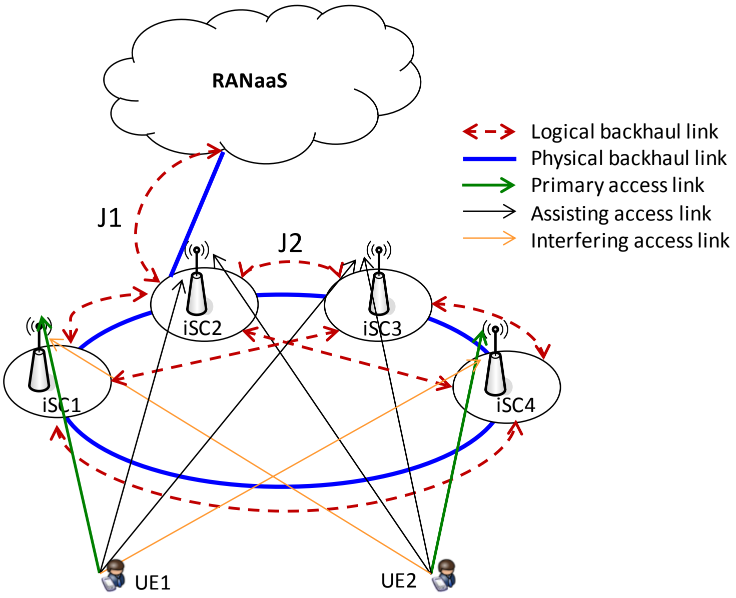

Figure 4-13: Two UEs are served by several iSCs, cooperating through In-Network-Processing.

4.8.2 Assumptions and requirements

The RRM (with included Cell Selection) needs to know the effective link quality of all access links between users and their serving virtual eNB to perform the actual MCS selection. If a measurement is not available yet, since no cooperation has been performed, an educated guess based on the separate physical link qualities has to be done. Furthermore, by evaluating the link qualities between the users and all iSCs in reach of the UE, the decision (which iSCs participate in the joint detection of this user) has to be taken by the iSC selection mechanism.

4.8.3 Expected Output

By using several iSCs for the detection of one UE, regardless whether this UE is using the same resources as another UE or not, an improvement of the effective link quality can be achieved, increasing throughput and decreasing the UE transmit power required. If a joint detection of several UEs using the same resources is performed, the area throughput is expected to grow significantly.

4.9 CT 3.9: Hybrid local-cloud-based user scheduling for interference control

4.9.1 Scenario Description

It is well known that RRM, especially in the form of optimized time-frequency resource allocation and user scheduling, can offer a strong weapon against interference limitations in wireless networks [112]. The key is the exploitation of various forms of diversity, i.e. time, frequency, space, and user diversity, through channel-aware and especially interference-aware scheduling.

In this contribution we are interested in tackling interference mutually generated among iSCs by resorting to channel state information (CSI) aware scheduling. The scheduling protocol can be seen as complementary to the signal-processing based interference coordination schemes investigated in WP2.

Similar to what is happening at the PHY layer, the interference generated from a total reuse of the spectral resources across neighboring iSCs can in principle be handled through cloud-based processing of all CSI data. For instance in a network with M iSCs, for each time frequency resource block, a scheduler can select the set of M most spatially compatible users to co-exist in the resource block. Asymptotic performance analysis suggests that multi-cell interference can be made to decrease quite substantially (although not totally) if a sufficiently large pool of active users is available for selection in all cells [113]. This analysis assumed centralized processing, or similarly cloud RAN processing based on complete and perfect CSI data being available in the RANaaS.

A complete treatment of interference in the cloud requires a significant overhead in terms of CSI data. More importantly this approach ignores the local processing capabilities of each iSC. In fact, each iSC can be made to collect relevant local information regarding SINR data for their users. In this CT, we suggest to split the multi-cell scheduling task into two complementary steps.

In the first step, we make use of local CSI in order to perform a first layer of scheduling (user selection) based on mostly local CSI, or CSI obtained from direct inter-iSC communication between neighboring cells. The resource allocation pre-selection decision is communicated to the cloud along with relevant multi-cell CSI data for the pre-selected users. A final scheduling decision is then taken in the cloud among the candidates identified in the first phase for each resource block. This process allows for adapting the level of centralized scheduling to the available bandwidth of the backhaul links.

A team decision theoretic problem

Our ongoing approach consists in doing a first pre-selection locally while the final scheduling decision is taken in the RANaaS. However, this corresponds only to a heuristic approach and it also does not fully exploit the backhaul architecture since the J2 links are not used. Future works will aim at leveraging the tool of game theory, team decision theory [112], and coordination theory [113]. Indeed, this problem can be seen either as a team decision problem where the iSCs and the RANaaS aim at achieving a global common objective based on different information, but it can also be seen as a coordination problem where the iSCs aim at coordinating their scheduling actions based on limited exchange. These new models of the scheduling problem lead to a new approach and have the potential to lead to a novel non-conventional split of the scheduling between the RANaaS and the iSCs. In particular, using more advanced tools could bring us closer to statements over the optimality of the approach used.

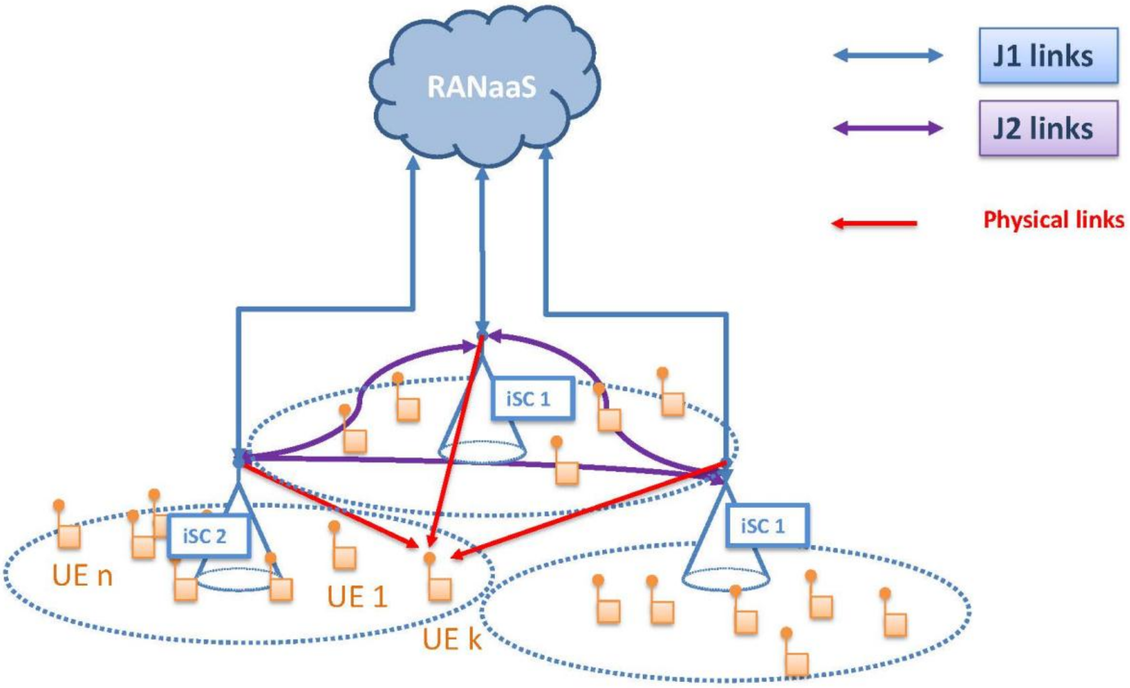

Figure 4-14: Scheduling for joint precoding in a hybrid architecture with both J1 and J2 links allowing for exchange of CSI and coordination of the scheduling decision.

4.9.2 Assumptions and requirements

We aim at coordinated scheduling, which entails some exchange of channel state information between interfering iSCs and the RANaaS. We assume that iSCs can collect local signal strength and also interference data from the UEs. To avoid the overhead related with a purely centralized cloud-based RRM processing, we assume that cloud-based processing can be complemented with a local pre-selection algorithm exploiting a layer of CSI information exchange over direct iSC-iSC links or completely local CSI.

The CSI and the index of pre-selected users by the various iSC is communicated to the RANaaS over finite capacity links. The final user selection is carried out in the RANaaS using this data and then sent back to the iSCs. The algorithm needs to be provided with information about the backhaul-link capacities (both J1 and J2 interface), user traffic demands, and coherence time of the radio channel.

4.9.3 Expected Outputs

The study is on-going. We anticipate a trade-off between locally run scheduling and scheduling processed in a centralized manner in the cloud. This trade-off will depend critically on the network size, number of active users, and backhaul link quality.

5 Logical and Functional Architecture

The iJOIN framework is mainly based on two concepts: the RANaaS concept and the joint optimization of the RAN and backhaul network. WP3 aims to develop MAC functionalities based on these paradigms to greatly enhance performance in the current standard of mobile communications.

The RANaaS is a cloud-based platform where the RAN protocols are centrally executed to the benefit of computational, coordination, and complexity gains. In the iJOIN vision, the RANaaS and a set of iSCs form the virtual eNB (veNB), which enables a flexible and dynamic functional split of the RAN protocols. It is important to note that physically the veNB may be composed by several iSCs cooperating with each other. Furthermore, the functional split between the cloud platform and the iSCs is controlled by the iJOIN virtual eNB Controller (iveC) located in the RANaaS. This logical entity uses information on the momentary status of the network (QoS, load, backhaul constraints, etc.) to perform an efficient functional split. Exchange of information between iSCs and the RANaaS (and the iveC) is enabled through the iJOIN J1 interface, and iSCs are connected with each other via the iJOIN J2 interface.

In D2.1 [27], the PHY layer processing of signals transmitted and received by the iSCs is described. As a consequence of the dense deployment, a geographical area is covered by several iSCs. Thus, joint transmission and detection schemes enabled by distributed processing among the iSCs and centralized processing within the RANaaS can be exploited. This allows for new and evolved PHY approaches, where some functionality will be executed in the iSCs and other parts may be implemented in the RANaaS.

With respect to the joint RAN/BH design, the goal of this WP is threefold: first, to elaborate mechanisms that take into account the non-ideal characteristics of wireless backhaul solutions used for small cell networks i.e. by limiting the amount of signaling required for inter-cell cooperation. Second, we aim to assess the performance of the proposed strategies in scenarios where the RAN can be limited by backhaul latency and capacity. Finally, also the functional split mechanism between the RANaaS and the iSCs has to be explored in detail in order to be able to maintain QoS under various backhaul conditions.

The information exchanged between the RAN entities over the J1 and J2 interface will depend on each CT. The different functional split options of a CT may require different signalling. In the next section we describe the input and output parameters of each CT considered in WP3. Then, in Section 0 we integrate this information to identify the interactions between CTs as well as the exchange of information within a network which is based on the iJOIN architecture.

5.1 Input and Output Parameters

Table 5-1and Table 5-2 describe the input and output information required by each CT. They list the related CTs, requested input information or provided output information, the sink or source of information in terms of CT and logical network entity, and it lists the parameterization of the interface. Furthermore, Table 5-3 describes each acronym and we indicate whether the related parameter is already defined in 3GPP LTE or has been introduced by iJOIN.

Table 5-1: Required Input of WP3 CTs

IP	CT	Requested Input	Source of Information		
			CT or system function	Logical network entity	Parameters
I3.1	3.1, 3.5 3.8	BH Routing Table /Info	C.T. 4.4	iNC	<src_address> <gateway> (nexthop) <dst_address>
I3.2	3.1, 3.2 3.3 3.8 3.9 3.7 3.5 3.4	BH state information (iSC-iSC, iSC-iTN) • SINR • Max Capacity • Remaining Capacity	Measurements iTN	iTN	<BH_SINR>, <BH_MAX_CAP>, <BH_RES_CAP>
			Measurements report iNC	iNC	<BH_ID>, <BH_SINR>, <BH_MAX_CAP>, <BH_RES_CAP>
I3.3	3.1, 3.2, 3.3, 3.4, 3.5, 3.7	QoS parameters per bearer (e.g. max. bit rate (MBR), guaranteed bit rate (GBR), packet delay budget (PDB))	RRC	veNB	<MBR>, <GBR>, <PDB>
I3.4	3.2, 3.3, 3.4, 3.5, 3.7, 3.8, 3.9	Channel state information per UE (DL/UL) (CQI,RSRP,..)	RRC (measurements)	veNB	<WCQI>, <SCQI>, <PMI>, <PTI>, <RI>, <RSRP>, <RSRQ> [116] [117]
I3.7	3.3, 3.4, 3.5, 3.7	Cell ID (to which cell the UE is currently connected, or which is the current location of the UE (depending on the RRC/ECM state))	In RRC_CONNECTED state: RRC (ECGI) In RRC_IDLE state: MME (last known ECGI)	veNB/MME	<ECGI>
I3.10	3.2	Scheduling policy (i.e., MCI, EDF,PF)	Scheduling	NMS	<SCHED_POL>
I3.11	3.3, 3.5, 3.9 3.7	Current buffer size • DL • UL	MAC (BSR)	veNB	<UL_BSR>, <DL_BSR>
I3.12	3.4	RNTI	RRC	veNB	<RNTI>
I3.13	3.4	iSC → RANaaS (J1): Quantized CSI	RRC	iSC	<BH_ID>, <BH_QUANT_CSI>
I3.14	3.4 3.5	iSC ←→ iSC (J2): Interference coordination information	CT 3.4	iSC	<RNTP> [118]
I3.16	3.5, 3.7	Latency backhaul (iSC->iSC; RaaS-iSC)	Measurements iTN	iNC	<BH_LAT>
			Measurements report iNC	iTN	<BH_ID>, <BH_LAT>
I3.18	3.7	UE mobility state information	RRC	veNB	<UE_MSE>
I3.21	3.7	UE capability (category …)		veNB/MME	<UE_CAP>
I3.22	3.2	Cell neighbouring list	RRC or OAM	veNB or SON	Array of <ECGI>

Table 5-2: Required Output of WP3 CTs

OP	CT	Provided Output	Sink of Information		
			CT or system function	Logical network entity	Parameter
O3.1	3.1	BH Link Selection	Scheduling	iTN	<BH_ID>
O3.2	3.1, 3.3, 3.9	RRM information (allocation of resources per BH link)	Scheduling	iTN	<BW>, <BH_FREQ>
O3.3	3.2, 3.3, 3.4, 3.5, 3.7, 3.8, 3.9	Resource allocation per UE (RBs, …)	Resource Mapper (e.g. in CT 2.1)	iSC	<SFN>, <DCI>
O3.4	3.2 3.8	iSC-UE mapping	CT2.3.2.1/RRC	veNB	<UE_ID>,array of <ECGI>
O3.5	3.3, 3.4, 3.5, 3.9	MCS (access)	T2.3 Scheduling	iSC	<MCS>
O3.6	3.4, 3.7	RANaaS → iSC (J1): Long term/coarse grained resource schedule	Scheduling	iSC	<LT_SCHED>
O3.7	3.5	Cell DTX pattern (for both U/C planes)	Scheduling	veNB	<DTX_PATTERN_ID>
O3.8	3.7	Local or Centralised computing	CT2.2	iSC	<SPLIT_CONF>
O3.9	3.7	Per iSC: • pair of (iSC-UE) involved in the turbo processing	CT2.2	veNB	Array of pair (<iSC_ID>, <UE_ID>)
O3.11	3.8	List of cooperating iSCs per iSC with max. bandwidth	CT2.1	iSC	Array of <iSC_ID>-<BH_MAX_CAP > tuples per iSC

Table 5-3: List of Abbreviations

Abbrev	Full Name (including explanation if necessary)	LTE or CT specific
Identifier		
BH_ID	Backhaul link identifier (for logical network)	iJOIN
BH_SINR	Backhaul link SINR	iJOIN
BH_MAX_CAP	Maximum backhaul link capacity (kbps)	iJOIN
BH_RES_CAP	Residual backhaul link capacity (averaged, kbps)	iJOIN
ECGI	cell ID	LTE
UE_ID	Unique identifier of an UE	iJOIN
MBR	Maximum Bit Rate (bps)	LTE
GBR	Guaranteed Bit Rate (bps)	LTE
PDB	Packet Delay Budget (ms)	LTE
WCQI	Wideband CQI	LTE
SCQI	Subband CQI	LTE
PMI	Index of precoding matrix (TS 36.213)	LTE
PTI	Index of precoding type (TS 36.213)	LTE
RI	Rank indication (TS 36.213)	LTE
SCHED_POL	Scheduling policy in iSC (e.g. RR, PropFair)	iJOIN
UL_BSR	Uplink buffer state report	LTE
DL_BSR	Downlink buffer state report	iJOIN
RNTI	Radio Network Temporary Identifier	LTE
BH_QUANT_CSI	Quantized backhaul CSI	iJOIN
RNTP	Relative Narrowband Transmit Power (TS 36.413)	LTE
BH_LAT	Backhaul link latency (ms)	iJOIN
UE_MSE	UE mobility state (depending on velocity) (high, medium, low)	LTE
UE_CAP	UE capability	LTE
SFN	System Frame Number	LTE
DCI	Downlink Control Information	LTE
UCI	Uplink Control Information	LTE
MCS	Modulation and coding scheme for access	iJOIN
DTX_PATTERN_ID	ID of cell DTX pattern	iJOIN
LT_SCHED	Long term/coarse grain resource schedule (FFS)	iJOIN
SPLIT_CONF	Indicates functional split configuration to CT	iJOIN

Interaction of CTs

This section aims to describe the interactions between CTs related to WP3 as well as the interaction of WP3 with WP4 and WP2. Accordingly, we will be able to identify the information carried by the functional interfaces, which enable the implementation of functionalities developed in WP3.

The WP3 CTs are listed in Table 5-4 and are classified accordingly to their specific objectives. In particular, CTs 3.1, 3.2, and 3.3 are part of the SON functionalities as they adapt the system parameters to changes in the cellular network, due i.e. to the network load, energy constraints, and mobility. CTs 3.4, 3.5, and 3.9 are devoted to enhance the performance of downlink transmissions by increasing spectral efficiency, mitigating inter-cell interference, and coordinated RRM.

Finally, CTs 3.7 and 3.8 increase the robustness of uplink transmissions by using inter-cell cooperation and exploiting spatial diversity. CT3.6 is devoted to investigate the iJOIN Utilization Efficiency metric, which enables to assess the improvements of the proposed CTs. Hence, it is not a technology as such and therefore is not represented in Figure 5-1. All the CTs are directly linked to the iJOIN veNB controller (iveC), which is charge to optimize the system performance by adapting the actual functional split to the current status of the network.

Table 5-4: iJOIN RRM/MAC Candidate Technologies (CTs)

CT	Topic	Abbreviation	Functional Block
3.1	Backhaul Link Scheduling and QoS-aware Flow Forwarding	BH Manager	SON
3.2	Partly decentralized mechanisms for joint RAN and backhaul optimization in dense small cell deployments	Coordinated Cell Selection	SON
3.3	Energy-Efficient MAC/RRM at Access and Backhaul	EE RRM	SON
3.4	Computational Complexity and Semi-Deterministic Scheduling	SD Scheduler	DOWNLINK
3.5	Cooperative RRM for Inter-Cell Interference Coordination in RANaaS	Coop. RRM	DOWNLINK
3.6	Assess and Increase Utilization and Energy Efficiency	n/a	n/a
3.7	Radio Resource Management for Scalable Multi-Point Turbo Detection	MPTD RRM	UPLINK
3.8	Radio Resource Management for In-Network-Processing	INP RRM	UPLINK
3.9	Hybrid local-cloud-based user scheduling for interference control	HL Scheduler	DOWNLINK

In addition to the three main WP3 blocks discussed above, we identified basic functions that include standard functionalities for the BH and RAN management, which support the iJOIN RRM/MAC enablers. In particular, the RRC includes all procedures related to mobility management and measurements such as RSRP and the serving cell information. The Scheduler function is devoted to map available radio resources to service requests according to a given policy. The MAC function is responsible for the data management on individual radio bearers such as block size, QoS management, and buffer management. Finally, the eICIC function allows for alleviating the effect of co-channel interference on both data and signaling by means of inter-cell coordination. These basic functions are placed next to the WP3 main block to underline the main contribution of this WP.

Figure 5-1 represents the interactions of the 4 main blocks which are under investigation in WP3 (the blue box) as well the exchange of information between with WP4 (in red) and WP2 (in green). From WP2, we take into account input and output information from the two main blocks, namely RAN-PHY Functions and BH-PHY Functions.

WP3 provides to WP2 RRM and MAC information concerning the radio access and the backhaul, like scheduling maps and link adaptation parameters; WP2 forwards to WP3 estimated radio and backhaul channel information such as SNR and user data after detection and decoding.

The exchange of information between WP3 and WP4 can be divided across two iJOIN logical entities: the iNC and the iTN. WP4 provides to WP3 information about the backhaul configuration and measurements such as routing information and mobility information.

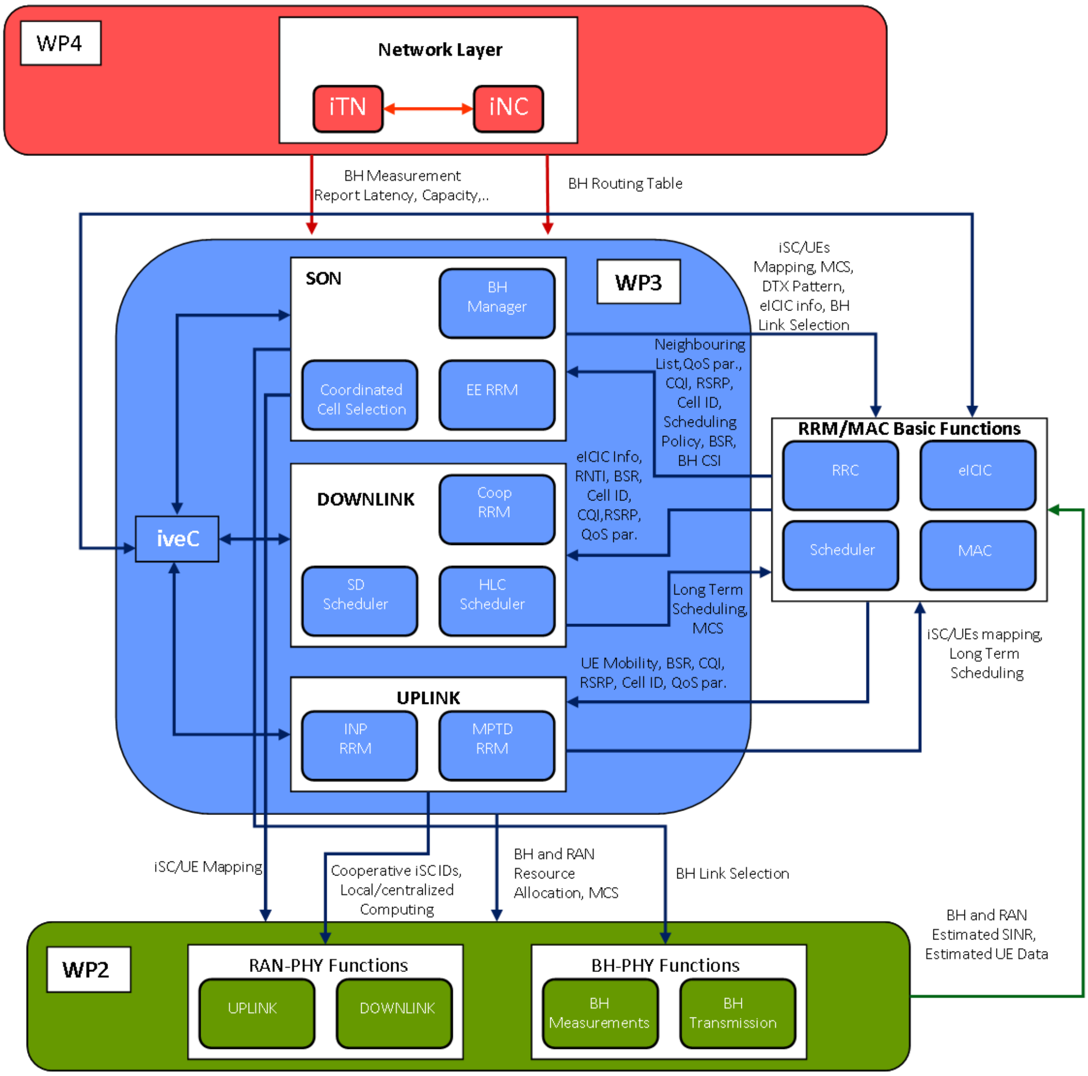

Figure 5-1: Functional interactions from WP3 perspective.

5.2 Function placement in logical architecture

In this section we continue the description of the MAC/RRM functions implemented in the iJOIN architecture, and we give a first overview of the physical placement of these functions. The placement of the functions that characterize a CT is mainly dependent on the implemented functional split option (i.e., the scheduling can be either implemented at the RANaaS or at a single iSC or even distributed amongst neighbouring iSCs that may belong to the same veNB). Although at this stage of the work we can neither identify all the possible functional split options nor the best one, we have been able to locate where the outputs of the CTs are sent and processed and which is the source of given CT inputs.

In Figure 5-2, we show the interactions amongst the WP3 CTs and other RRM/MAC functions located at the veNB and at the iNC. As for the previous section, we have identified three main groups of CTs: Downlink, Uplink, and SON. At the centre of the figure, we can distinguish the iJOIN veNB, which is made up of the iSC, the RANaaS platform, and the iTN. Furthermore, the veNB is also connected to the iNC, which has the role to collect information concerning both the backhaul network and RAN, and performs functionalities such as routing and load balancing.

At the bottom of Figure 5-2, the blocks of CTs generate information that is used at the veNB or at the iNC; on the contrary, the veNB and the iNC pass information to these three blocks in the top of the figure.

For instance, the Coordinated Cell Selection (CT 3.2) functions could be either implemented locally at the iSCs or in a centralized approach at the RANaaS; in any cases its functions receive BH measurement reports that is elaborated inside the iNC, and output the iSC/UE mapping to the veNB for i.e. the scheduling process.

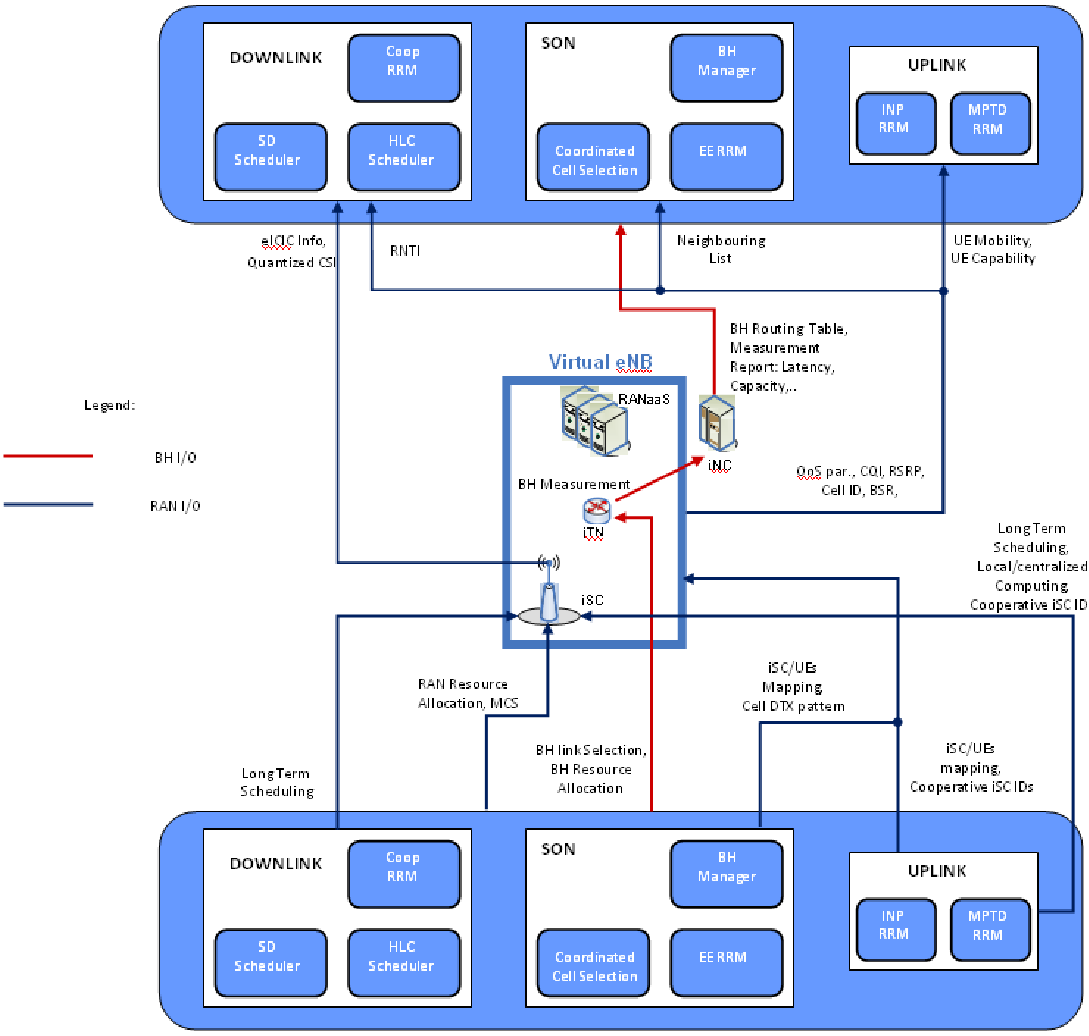

Figure 5-2: Functional interactions of the CTs with the iJOIN architecture.

5.3 General idea of functional split for WP3

From WP3 perspective, functional shift means moving native eNB functionality within iJOIN's veNB from the iSCs to the RANaaS layer. The purpose of such functional shift is to offload the iSCs from the related computational burden, executing such tasks on a general purpose, industry standard server based platform. The iSCs can so be relieved by part of their functionalities, enabling them to run on lower performance hardware and making their implementation more convenient, especially in dense or very dense deployment scenarios like the one targeted by iJOIN. On the flip side, the challenges stay in the latency introduced by the communication between iSCs and RANaaS layer over the J1 interface, which can be not compliant with the actual functional requirements, and/or impose specific constraints on the underlying backhaul link.

For each candidate technology, an evaluation of the benefits and constraints must be carried on, in order to pick one of the possible deployment options:

Local processing	The computational tasks are executed in the iSCs, with no difference with respects to the standard eNB case
Cooperative processing	The computational task is split between the iSCs and the RANaaS, being partially executed in each of the two. This option is viable when a functional breakup is possible.
Centralized processing	The whole computational task is offloaded from the iSCs to the RANaaS layer.

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 5-5: 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)	n.a.	High (if following frame creation)
Cell selection and Reselection	O(#UE)	Low	Low	Follows #cells	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, #cells)	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	n.a.	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 5-6: 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	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 retransmissions 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 granularity	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.

5.4 Functional Split for Candidate Technologies

In this section, we provide further details for each CT, giving particular attention to the possible functional split options, which are conceivable at this stage of the work. In particular, we define how the functional split(s) can be realized, the advantages of a given approach, and his challenges. Complexity, architectural impact, and overhead are investigated.

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

This CT discusses the BH Link Scheduling for a dense deployment of iSCs assuming multihop wireless BH between iSCs. This incorporates the activation/switching of BH links considering the BH channel conditions and subsequently the QoS-aware RRM (in BH) for the activated links.

The BH Link scheduling (activation/de-activation) is handled locally at the RANaaS. The RANaaS receives periodically (in coarse time-scale) routing information from the iNC so as to have knowledge of all the assigned paths towards all the involved iSCs. Moreover, the RANaaS receives the BH Channel Information in J1, which shows the channel conditions from each iSC towards all its neighbors. Based on this information, RANaaS schedules centrally which BH links are going to be active each time slot and forwards this information to the corresponding iSC. Here to mention that each iSC receives multiple packets from the core network towards multiple destinations, through the corresponding iTNs. Taking into account that the iSC is aware of which BH links are going to be active for the next time slots (previous step), it then schedules how to forward the traffic so as to ensure that the QoS requirements for different types of traffic are not violated.

In Figure 5-3, we illustrate the functional split for CT3.1. As described above, the main function, which is the BH link scheduling, is performed in RANaaS and based on this the traffic flow forwarding is performed by each iSC. In this case, J1 carries control information (C-plane) between iSC and RANaaS and J2 carries data (U-plane) between iSCs at the local backhaul (intra-veNB BH).

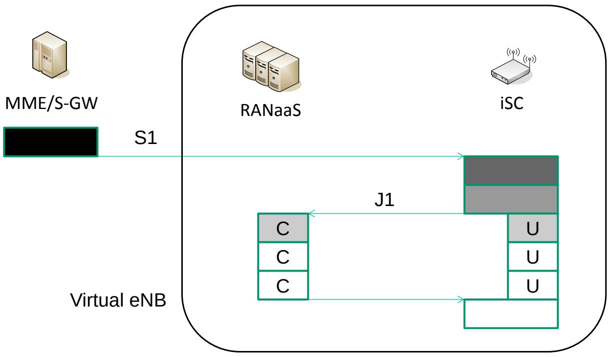

Figure 5-3 Illustration of functional split for CT3.1.

Table 5-7: Assessment of functional split impact for CT3.1

Functionality	**RRM in RANaaS**
Computational Needs	Locally Centralized BH Link Scheduling at RANaaS; Distributed flow forwarding decision at iSC
Centralization Cost/Impact	Cost: BH CSI, BH routing info required at RANaaS Impact: Lower overhead than fully centralized BH scheduling
Centralization Benefits	Activation/de-activation of BH links is performed in a holistic manner to optimize BH network capacity in a cluster of iSCs
Computational Diversity	High
Latency req. on interface	Low latency required in J1 and J2
Bandwidth req. on interface	High bandwidth in J2; low-to-medium in J1
3GPP impact	n/a
Link reliability req.	High
veNB impact	Intra-veNB BH link scheduling, flow forwarding
C-plane / U- plane	U-plane in J2, C-plane in J1

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

In this CT, the RRC procedures can be flexibly moved from the iSC to the RANaaS: in the case where this protocol is managed at the iSC, the cell (re)selection mechanism, connection establishment steps, mobility management, etc, are implemented in a distributed way, which limits overhead, latency, and system complexity but also results in limited network performance. On the contrary, in the centralized approach, the CT3.2 profits of the global knowledge of the RANaaS on the network status to implement these procedures such that the overall network capacity is optimized. In particular, this approach can exploit information on the average cell load, backhaul availability, etc. However, centralizing the RRC mechanisms is not expected to be always beneficial. Hence, the proposed system is able to observe the current status of the network in terms of active users and activated iSCs, and consequently to decide whether to implement the cell (re)selection locally or in the RANaaS.

Figure 5-4 illustrates the functional split as it is applied by this CT. The CT does not apply any changes to the processing of user-plane data. It only affects the cell (re)selection process, but not the data-plane. Regarding the control plane, the cell (re)selection may imply some handover action which can be directed by the RANaaS or the involved iSC depending on the functions integrated into the RANaaS.

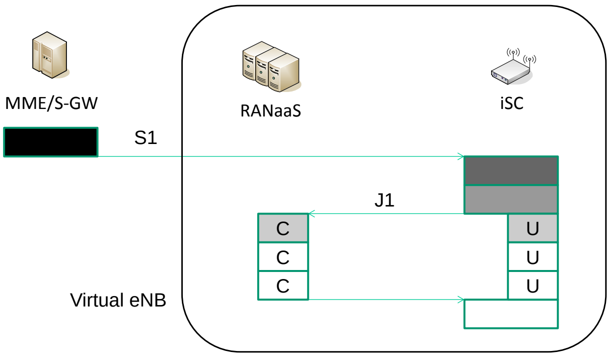

Figure 5-4: Illustration of functional split for CT3.2.

Table 5-8: Assessment of functional split impact for CT3.2

Functionality	**RRC in RANaaS**
Computational Needs	Mainly focused on the RANaaS, the specific computational load can vary depending on the specific algorithm executed to perform the cell (re)selection
Centralization Cost/Impact	CSI measurements required at RANaaS
Centralization Benefits	Centralization can exploit the differences in the backhaul and access resources of the iSCs to maximize global performance
Computational Diversity	High
Latency req. on interface	Low latency requirement to perform handovers
Bandwidth req. on interface	Intermediate bandwidth requirements (CSI measurements)
3GPP impact	No impact
Link reliability req.	Medium
veNB impact	Selection algorithm performed at RANaaS, (re)selection performed as a handover in the involved iSCs.
C-plane / U- plane	C-plane

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

In this CT, we aim to enable energy efficient operations at iSCs by enabling dynamic and fast activation/deactivation of small cells. By splitting data and control planes, the control plane is managed at the RANaaS, which coordinates the iSCs state, enable the establishment of connections, implements the mobility functionalities, and guarantees the network coverage. Henceforth, iSCs could continuously deactivate their functionalities in absence of active users to serve and stay active only when there is data to send.

The proposed architecture for implementing the U/C plane functional split is presented in Figure 5-5.

In this framework, the RANaaS is aware of the iSCs position and it exploits received signalling from the eNB (on the UE location, the cell load, etc.) to determine if one or multiple iSCs have to be activated. Accordingly, as shown in the right side of Figure 5-5, the iSCs are switched on and start to transmit a discovery signal synchronously with the eNB signal. Note that such synchronization can be enabled either through the J1 interface (through the RANaaS).

Furthermore, the UEs close to an iSC receive from the associated eNB a message that asks to measure and report the discovery signal originated from the iSC. We give an example of connection establishment procedure in Figure 5-6.

On the left side of Figure 5-5, we can see as only part of the C plane protocols are moved to RANaaS: in fact in this CT, we consider that the RRC functionalities are managed by the RANaaS. On the contrary, in CT 3.5 we extend this idea by integrating also part of the MAC protocol in the RANaaS, to enable coordinated RRM and limit the effect of the inter-cell interference.

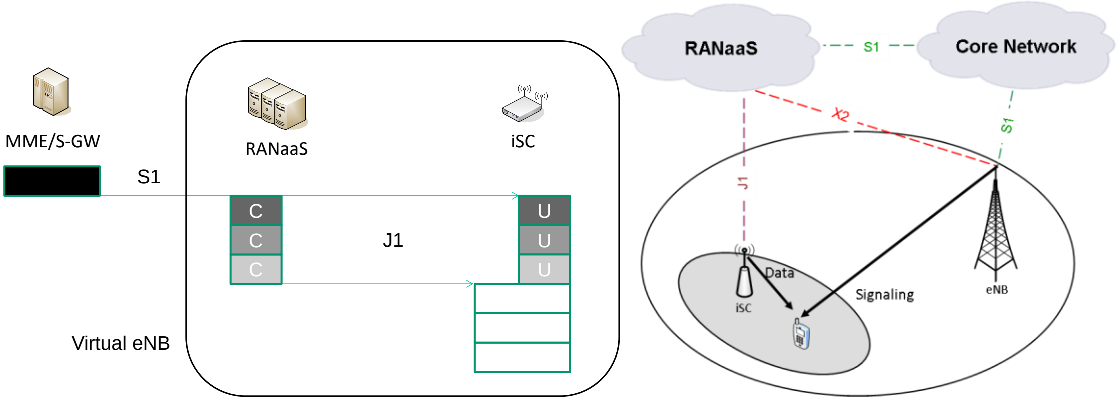

Figure 5-5: The proposed architecture for the U/C plane functional split.

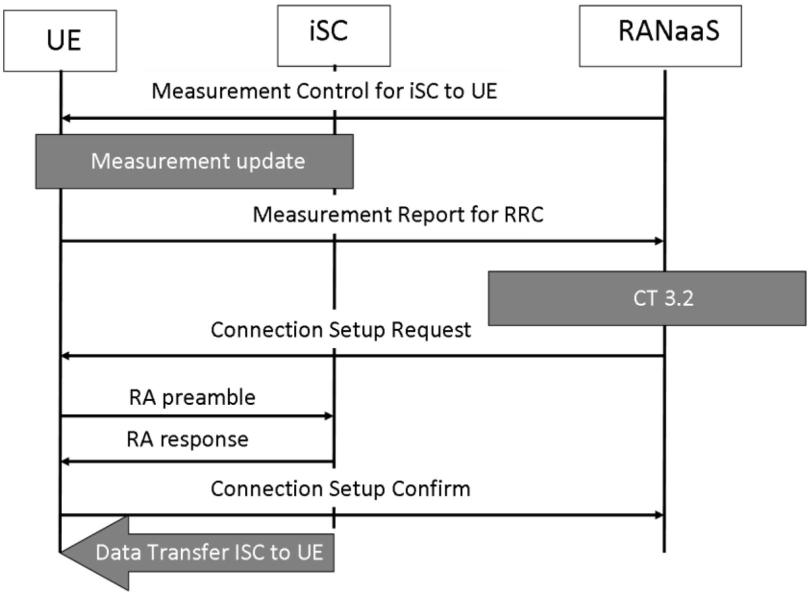

Figure 5-6: The iSC-UE connection established procedure supported by the RANaaS.

Finally, we describe the foreseen advantages and challenges for this CT at this stage of the work in Table 5-9.

Table 5-9: Assessment of functional split impact for CT3.3

Functionality	**RRC in RANaaS**
Computational Needs	O(#cells)
Centralization Cost/Impact	High (architecture modification)
Centralization Benefits	Energy saving, load balancing, mobility enhancement
Computational Diversity	n.a.
Latency req. on interface	Low latency required for mobility
Bandwidth req. on interface	Low requirements
3GPP impact	Splitting is under study under REL-12
Link reliability req.	High
veNB impact	Modification in the LTE architecture
C-plane / U- plane	C/Plane is mainly affected

5.4.4 CT 3.4: Computational Complexity and Semi-Deterministic Scheduling

CT 3.4 will allow for scaling the complexity of the central and the local scheduler by varying the average number of UEs per bin, the resource granularity, the CSI granularity, and the computational load in both stages. In fact, the proposed two-stage scheduler can be flexibly operated between the two extreme cases of fully centralized scheduling and fully decentralized scheduling based upon the channel parameters and backhaul parameters. Furthermore, the algorithm allows for adopting the computational load and backhaul overhead to the current system state. Finally, the CT allows for changing the central scheduler quickly in order to implement different scheduling policies and algorithms depending on the scenario and supported services.

Figure 5-7 illustrates the functional split as it is applied by this CT. The CT does not apply any changes to the processing of user-plane data. It only affects the resource allocation strategy for each radio access point but not the actual control-plane or data-plane. The final scheduling is performed at the iSC and therefore the actual control-channel data is defined locally at the iSC, even in the case of a one-to-one mapping at the iSC.

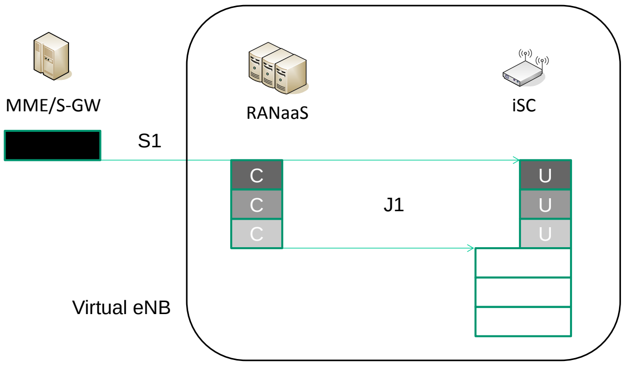

Figure 5-7: Illustration of functional split for CT3.4.

Table 5-10: Assessment of functional split impact for CT3.4

Functionality	**RRM in RANaaS**
Computational Needs	Distributed across RANaaS and iSC; pre-processing for ICIC at RANaaS, link-adaptive scheduling at iSC
Centralization Cost/Impact	Cost: CSI measurements required at RANaaS Impact: ICIC at lower overhead costs than fully centralized scheduler
Centralization Benefits	Flexible degree of centralization depending on CSI quality and latency; Benefits for ICIC and through exploiting computational power at RANaaS
Computational Diversity	High
Latency req. on interface	Flexible → algorithm shall adapt to latency
Bandwidth req. on interface	Low to Medium → only CSI measurements on sub-bands required
3GPP impact	No impact foreseen
Link reliability req.	High, otherwise scheduling decisions are not communicated to iSC
veNB impact	Scheduler of veNB distributed across two entities
C-plane / U- plane	No impact on actual user/control data but only RRM, i.e. scheduling

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

In this CT, J1 carries channel state information per UE from iSCs to the RANaaS entity (long term CSI). The RANaaS creates a graph that consists of users (vertices) and their interference conditions (edges). The RANaaS entity then partitions the UEs into clusters to mitigate ICI and dynamically allocates resources to these clusters.

Thereafter, J1 carries the RRM information from RANaaS to the corresponding iSCs and each iSC allocates the resources to its enclosed users. Figure 5-8 illustrates the functional split for the proposed inter-cell RRM mechanism, which is performed in a systematic way in RANaaS (intra-veNB).

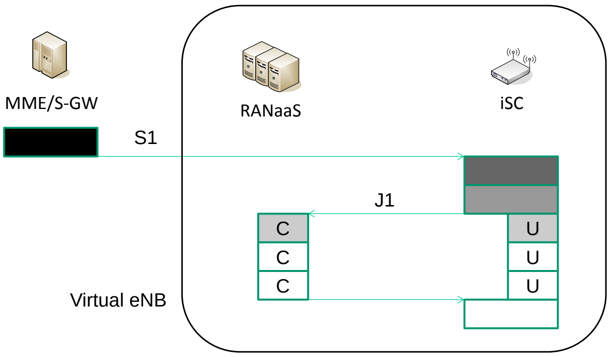

Figure 5-8 Illustration of functional split for CT3.5.

Table 5-11: Assessment of functional split impact for CT3.5

Functionality	RRM in RANaaS
Computational Needs	Locally centralized inter-cell RRM at RANaaS
Centralization Cost/Impact	Cost: CSI measurements required at RANaaS Impact: Lower signalling overhead using localized ICIC, than fully centralized scheduler
Centralization Benefits	Holistic/systematic inter-cell RRM for a cluster of iSCs, within veNB; high computational gains in RANaaS
Computational Diversity	High
Latency req. on interface	Low latency on J1
Bandwidth req. on interface	Low → long-term CSI measurements per sub-channel
3GPP impact	n/a
Link reliability req.	High (resource allocations need to be fed-back to iSC)
veNB impact	RRM inside VeNB
C-plane / U- plane	C-plane

5.4.6 CT 3.6: Assess and Increase Utilization and Energy Efficiency

This candidate technology is not itself moving or splitting functionalities from the iSCs to the RANaaS. Its goal is instead to measure and assess the amount of efficiency obtained by means of specific functional shifts by other candidate technologies. For each functional split, the defined utilization and energy efficiency metrics are evaluated, and the results analysed to understand where the best efficiency improvements are, and which system parameters can possibly be tweaked for increasing these metrics.

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

In this CT, the RRM algorithm responsible of pairing iSCs and UEs will always be performed at the RANaaS platform. On-demand basis (i.e. based on a specific request of an iSC), it will provide to the iSCs involved in the turbo detection process the long term scheduling framework for the involved UEs. The UEs not taking part to a turbo processing procedure will still be handled solely by their serving iSCs.

The functional split will occur at the physical layer if the iSC-RANaaS link supports it and the RANaaS platform is available for computing purpose, otherwise the processing will remain at the iSC level with or without iSC-iSC exchange.

Variant CT3.7a: turbo-processing is performed at each iSC

- Used when the J1 interface is not sufficient to support quantized raw I/Q symbols (after iFFT) transmission (bandwidth or latency limited) **or** when the RANaaS platform is not available for PHY tasks.
- Equivalent to the Single-Point Turbo Detection (SPTD) described in D2.1 [27], which brings some gain even when no cooperation is done between the iSCs during the iterative detection procedure.
- However, cooperation through J2 interface could increase the performance by exchanging information (e.g., soft bits).

- Figure 5-9 shows the functional split for the UE involved in the turbo detection process, where scheduling is performed at the RANaaS platform (framework definition) and iSC (actual scheduling under the framework provided by RANaaS). The control plane is shared between these two entities.

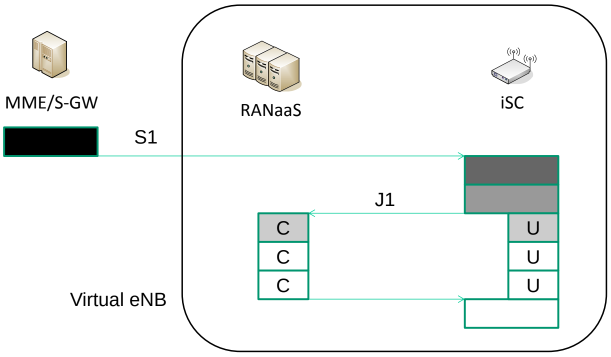

Figure 5-9: Illustration of functional split for CT3.7, variant a.

Variant CT3.7b: turbo-processing is performed at the RANaaS platform

- Used when the J1 interface is sufficient to support quantized raw I/Q symbols (after iFFT) transmission (bandwidth and latency) and when the RANaaS platform is available for PHY tasks.
- Equivalent to the Multi-Point Turbo Detection (SPTD) described in D2.1 [27], which brings significant gain thanks to the receiver diversity.
- Figure 5-10 shows the functional split for the UE involved in the turbo detection process. Control and user plane are processed in the RANaaS platform.

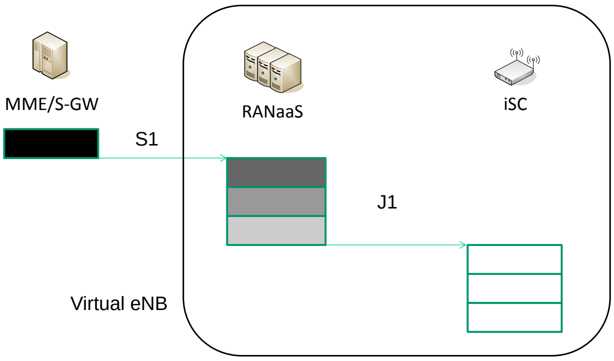

Figure 5-10: Illustration of functional split for CT3.7, variant b.

Table 5-12: Assessment of functional split impact for CT3.7

Functionality	Variant a	Variant b
Computational Needs	Distributed across RANaaS and iSC; scheduling framework at RANaaS, link-adaptive scheduling under framework at iSC	
Centralization Cost/Impact	Cost: CSI required at RANaaS, CSI and resource allocation required at iSC Impact: Lower overhead than fully centralized scheduler	Cost: CSI required at RANaaS Impact: ICIC at lower overhead costs than fully centralized scheduler
Centralization Benefits	Interference coordination and exploitation among iSCs and UEs allowing advanced signal processing	
Computational Div.	High	
Latency req. on interface	Medium latency required in J1 Low latency required in J2	Low latency required in J1
Bandwidth req. on interface	Low-to-Medium bandwidth in J1 Low-to-High bandwidth in J2	High bandwidth in J1
3GPP impact	n/a	
Link reliability req.	High	
veNB impact	Scheduler of veNB distributed across two entities	
C-plane / U- plane	No impact on actual user/control data but only RRM, i.e. scheduling	C and U plane going through the J1 interface

5.4.8 CT 3.8: Radio Resource Management for In-Network-Processing

The joint RRM and iSC selection mechanisms developed within this CT depend on each other's information and should therefore be implemented at the same location. Due to this, there exist 2 possible variants where to implement the functionality, implementation in RANaaS and implementation at iSC.

Variant CT3.8a: Implementation in RANaaS

In this variant, the RRM and the iSC selection takes place on a cloud platform for a set of iSCs. Within this set, it is not necessary that all iSCs are able to cooperate with each other. A pooling of physically separated iSC clusters is also possible. In this configuration, all the required information (physical and effective access link qualities, current backhaul state and load) has to be forwarded from the iSCs over the J1 interface to the RANaaS and the provided output for the iSCs needs to be transmitted back to the iSCs.

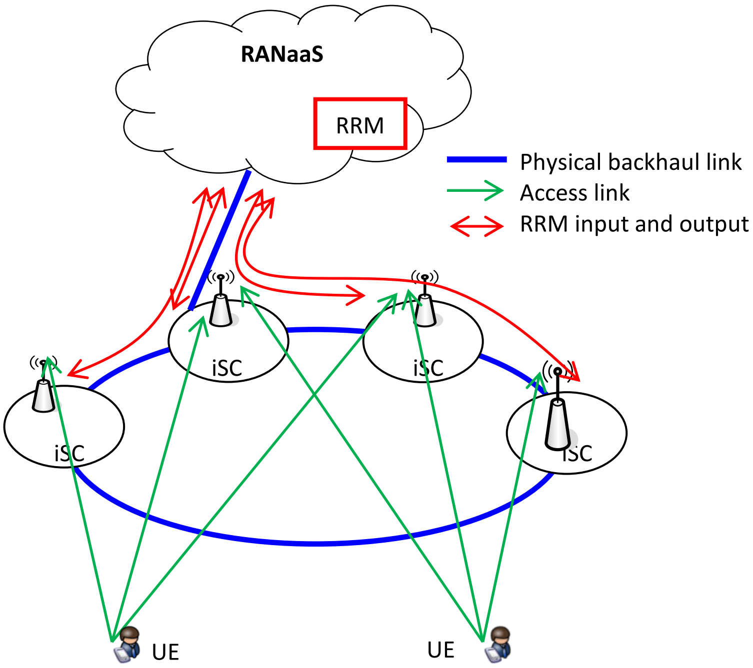

Figure 5-11: Example of information flow in case of centralised RRM.

The advantage of this variant is that some pooling gain can be achieved if the RRM of several iSC clusters is performed in the same entity. The disadvantage of this variant lies in the fact that for all required information a J1 link has to be set up between every iSC and the RANaaS. Depending on the backhaul topology, these logical links might be carried by a single physical link on which the load thus is increased. Furthermore, the J1 links might have a larger latency, which causes the information to be outdated when it reaches the RRM entity in the RANaaS, hindering the scheduling and affecting the performance.

Variant CT3.8b: Implementation at iSC

An alternative implementation can be done at one of the iSCs. Although approaches for distributed RRM exist, they are not scope of this CT. Therefore, one iSC needs to collect the required information on link qualities and backhaul. This has to be done over J2 links. Since not all iSCs might have a direct J2 connection established to the managing iSC, these links have to be established beforehand by another entity or a routing protocol is required over already established J2 links.

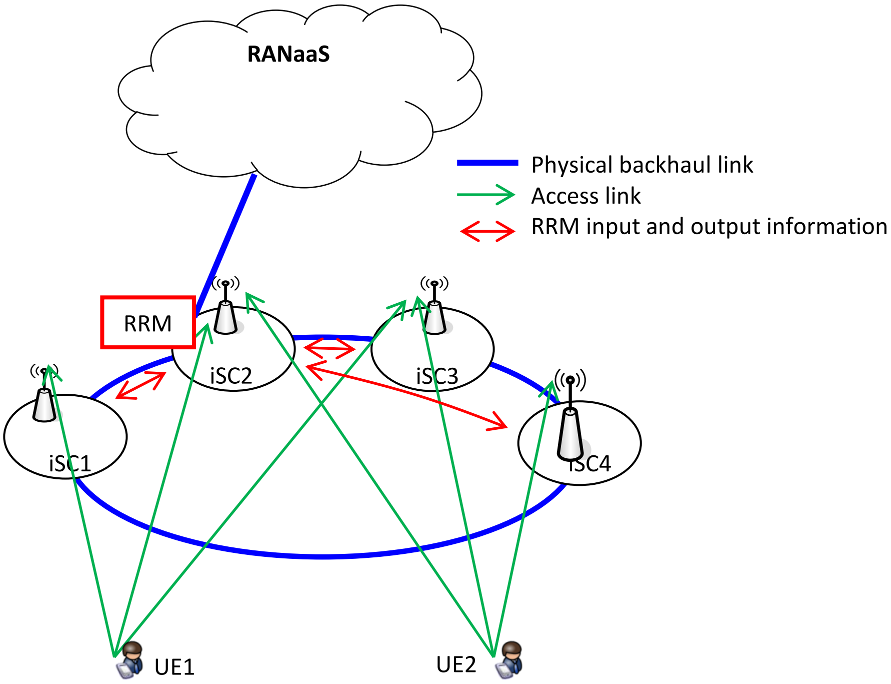

Figure 5-12: Example of information flow in case of RRM at iSC2.

The advantages of this variant basically correspond to the disadvantages of the other variant: Since information only needs to be exchanged among, iSCs, the J1 link is not employed and also the latency on J2 links is expected to be lower than on the J1 link.

As a disadvantage, it has to be determined at which iSC the RRM is performed. This decision might be influenced by the backhaul topology, load state and current clustering of iSCs. This should be implemented in the iJOIN Functional Controller (iFC).

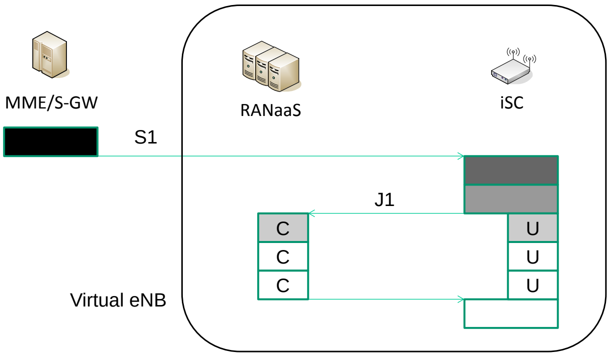

Figure 5-13: Mapping of CT3.8 functional split variant a to WP5 functional split architecture.

Figure 5-13 shows the mapping of this CT's functional split variant a to the general functional split architecture as defined in deliverable D5.1. While the processing of the user plane is e.g. performed at the iSC (but it might also alternatively be shifted to the RANaaS), the control plane processing, in particular the scheduling and resource allocation, is performed at the RANaaS.

Table 5-13: Assessment of functional split impact for CT3.8

Functionality	Variant a: RRM in RANaaS	Variant b: RRM at iSC
Computational Needs	Same, but RANaaS should have more processing power	Same, processing power at iSC limited
Centralization Cost/Impact	Increased traffic load on J1	n/a
Centralization Benefits	Pooling gain possible, also Inter-Cell RRM	n/a
Computational Diversity	Medium to high	n/a
Latency req. on interface	Low latency on J1 required for scheduling	Relatively low latency required on J2 (but can be expected)
Bandwidth req. on interface	Bandwidth required on J1	Bandwidth required on J2
3GPP impact	Scheduling needs to consider increased latency	None, group of iSCs may appear as VeNB
Link reliability req.	High (on J1)	High (on J2)
veNB impact	RRM inside VeNB	RRM inside VeNB
C-plane / U- plane	C-plane	C-plane

5.4.9 CT 3.9: Hybrid local-cloud-based user scheduling for interference control

This candidate technology aims at exploiting both the J1 and the J2 links in order to reduce the requirements on the iSCs and on the J1/J2 links. Hence, we aim at exploiting the backhaul links available. This means that the proposed hybrid scheduling will go smoothly from the scheduling being fully distributed at the iSCs in case the J1 links are weak and the iSCs have a sufficient processing power to the scenario where the processing is fully centralized at the RANaaS.

In WP2, CT 2.5 proposes a novel precoder design adapted to the same hybrid backhaul architecture studied here [27]. The precoder design proposed can also be implemented according to several different functional splits and the choice of the functional split for the precoder should be made in relation to the function split for the RRM since the functional split for the RRM determines the position in the network where the CSI relative to the user is provided. Yet, it is expected that the functional splits should be anyway similar since the requirements on the processing power and on the backhaul links follow the same pattern for the RRM and the precoder design.

In Table 5-14, 4 possible different functional splits are presented for the user scheduling in the case of joint precoding as described in CT 2.5. Configuration a) corresponds to the RRM being done in the RANaaS in a centralized way, configuration b) corresponds to the hybrid scheduling proposed, configuration c) corresponds a centralized scheduling being done at one master iSC while configuration d) corresponds to the RRM being implemented in a distributed manner at all the iSCs.

Table 5-14: Assessment of functional split impact for CT 3.9

Functionality	a)RRM in RANaaS	b) Hybrid RRC	c) RRM at Master iSC	d) RRM distributed at iSCs
Computational Needs	Strong at RANaaS	Shared between RANaaS and iSCs	Strong at master iSC	Shared among all iSCs
Centralization Cost/Impact	Strong	Limited	strong	low
Latency req. on interface	Low latency on J1 required for scheduling	Low latency on J1/J2 required for scheduling	Low latency on J2 required for scheduling	Relatively low latency required on J2 (but can be expected)
Bandwidth req. on interface	Large (J1)	Intermediate (J1/J2)	Bandwidth required on J2	Bandwidth required on J2
3GPP impact	None, group of iSCs may appear as veNB	None, group of iSCs may appear as veNB	None, group of iSCs may appear as veNB	None, group of iSCs may appear as veNB
Link reliability req.	High (on J1)	low (on J1/J2)	High (on J2)	Low (on J2)
VeNB impact	RRM inside VeNB	RRM inside VeNB	RRM inside VeNB	RRM inside VeNB
C-plane / U- plane	C-plane	C-plane	C-plane	C-plane

Figure 5-14 illustrates the functional split as it is applied by this CT in the variant **a**. The CT does not apply any changes to the processing of user-plane data. It only affects the resource allocation strategy for each radio access point but not the actual control-plane or data-plane.

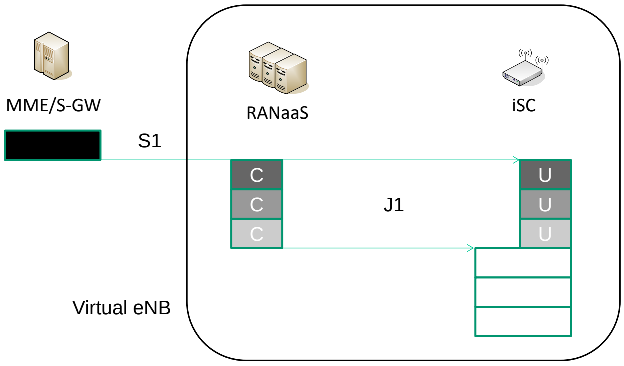

Figure 5-14: Illustration of functional split for CT3.9 variant a.

5.5 Further examples on the functional split

To present the concept of the functional split in more details and assess potential gains and challenges, we discuss in this section how cell (re)selection, inter-cell RRM, and segmentation/reassembly functionalities can profit of this paradigm. The general goal of this approach is to shift from the iSCs some functionalities and related computational burden, executing them centrally in the RANaaS platform. Henceforth, centralization may result in higher performance due to the better knowledge on the network status (i.e. for cell (re)selection and inter-cell RRM) or to the balancing of the computational load (such as for the segmentation/reassembly).

5.5.1 Cell (re)selection

Description of Functionality

Cell (re)selection functions are located in the RRC protocol, which belong to the control plane protocol stack. This process allows selecting for each UE the best cell that can serve it. For this purpose, each UE measures the signal strength of the different surrounding cells at the PHY layer. Depending of the state of the RRC protocol (RRC_IDLE and RRC_CONNECTED), the cell selection process differs substantially.

RRC_IDLE is an energy saving state, where the number of process required at the UE is limited. In this state, the network does not known the UE position at a cell level, the unicast data transfer is not possible, and the cell (re)selection is performed completely by the UE. In RRC_IDLE, the scope of the cell selection is to find a cell on which camp on, i.e., to receive system information, to allow to switch to RRC_CONNECTED state and to receive paging messages. The process followed by an UE to perform the cell selection is the following one.

First, UE's RRC layer asks PHY layer to scan frequencies and report the surrounding cells. Once the UE PHY has performed this scan to find the supported frequencies and cells, it reports the results to the UE RRC layer, indicating for each detected cell its Cell ID and the following Cell Specific Power values:

- Reference Signal Received Power (RSRP), which measures the *cell signal strength*
- Reference Signal Received Quality (RSRQ), which is used jointly with RSRP from REL-9. It is defined as the ratio of the RSRP and the carrier RSSI; hence, it gives an information on the *cell signal quality*

Based on these values, the UE RRC will select the strongest Cell ID from the list and then will go for the Cell validation procedure. In case of **cell range-expansion,** the serving cell of a UE is selected according to the following criteria: Cell_ID = $\mathrm{argmax}_{\{i\}}$ $\{RSRP\_i + bias\_i\}$, where *bias_i* has a positive value for picocells. Once the selected Cell ID passes the cell validation procedure, the UE camps onto it and proceeds to decode the broadcast information (MIB, SIBs) of the cell [114].

Additionally, the UE shall regularly search for a better cell to perform a cell reselection. This procedure enables a UE to make measurements on neighbouring cells and permit efficient handover between then. The cell reselection procedure is triggered by the system according to the serving cell quality level and the threshold indicated in the system information.

On the contrary, in RRC_CONNECTED state, the UE location is known on the cell level, unicast data transfer is possible, and the UE mobility is controlled by the network. In this state, the source eNB configures the UE measurements and reports. Based on these reports, the source eNB decides if the handover process should be initiated or not. Once the handover process is initiated by the source eNB, the admission control is performed at the target eNB, which has to send a handover ACK to the source eNB. On receiving this ACK, the source eNB sends a handover command to the UE and it also starts to send data to the target eNB as well. Finally, the UE sends a handover confirmation to the target eNB, which updates the location information to the core network.

Therefore, in RRC_CONNECTED state, the cell (re)selection process is strongly related to the UE mobility management procedures, such as UE measurement configuration and reporting; and handover. Additionally, it is also related to QoS management functions, scheduling, and ICIC.

General challenges

The main challenge of the cell (re)selection process is that the current mechanisms that perform it are based solely on the power level received from neighbouring cells, without using information regarding the cell loads and backhaul capacities. Additionally, in RRC_IDLE state the procedure is managed completely at the UE.

For these reasons, centralization could provide high gain through holistic network optimization and higher QoE. This centralization would not impose stringent requirements for the backhaul between the small cells and the RANaaS in J1, although a low latency backhaul would be needed between low latency requirements for backhaul between small cells and small cell-RANaaS in J2/J1when the UE is in RRC_CONNECTED state. Finally, a central controller should be locally deployed.

Options for functional split

As stated previously, depending on the state of the UE (RRC_IDLE or RRC_CONNECTED), the process of cell selection is mainly performed by the UE (RRC_IDLE) under the procedure of cell (re)selection [114], [115], or by the network (RRC_CONNECTED) under the procedure of handover [3]. We focus mainly in this second option since it is the one that has more impact on the UE perceived service and the network capacity.

In LTE Rel. 9, the handover procedure is always performed in two steps. First, the UE measures the signal levels (RSRP or RSRQ) of the serving cell and its neighbours and send them to the serving eNB. Then, the serving eNB uses this information to decide on the handover and request it to the target cell. Based on this, there are two options to performing the functional split in iJOIN:

Split option A

In this option, the handover process is performed by the iSC with the aid of the RANaaS platform. The serving iSC will send the UE Measurement Report to RANaaS through J1. Based on this report (and with load information of the neighbouring cells), RANaaS will perform the handover decision and will send the decision back to the serving iSC. The serving iSC will initiate the handover procedure with the new serving cell sending a Handover Request through the J2 interface. Once this request is received, the admission control will be performed by the new iSC (maybe with the aid of RANaaS). The rest of the handover procedure is performed through the J2 interface (exchange of Handover Request Acknowledge and SN Status Transfer).

Split option B

In this option, the handover process is fully performed in the RANaaS. The serving iSC sends the UE Measurement Report to RANaaS through J1, which performs the handover decision based on this report and using the load information and backhaul restrictions of the neighbouring cells. This decision is sent to the serving iSC and the new iSC through J1. Additionally, the Handover Request to the new iSC and the admission control can be avoided since RANaaS also takes care of the admission control of the new iSC. The rest of the process corresponds to an intra-eNB handover (only sending of unacknowledged DL packets and out of sequence UL packets may be required through J2 if management of U-plane information is performed locally in the iSC). Finally, more complex solutions can be exploited if the reallocation of users of the new iSC is allowed.

Summary

The main benefit of centralization is that the cell selection process can take into account the load and backhaul restrictions of the neighbouring iSC, which will increase the global performance of the network. Additionally, the admission control performed in the new iSC can be avoided and a decrease in the in the signalling between surrounding iSCs can be achieved.

On the other hand, it must be noted that the complexity will be increased with the number of iSCs as well as with the number of UEs. Finally, a low latency backhaul is required to perform the handover. Nevertheless, this latency will be of the same order of the one required to perform a handover over an X2 interface.

Table 5-15: Summary of pros/ cons for the cell (re)selection options.

	Option A	Option B
Computational needs in iSC	Low	Low
Computational needs in RANaaS	Medium to high (depending on the specific algorithm executed to perform the cell (re)selection)	Medium to high (depending on the specific algorithm executed to perform the cell (re)selection)
Signalling Load in J2 (iSC-iSC)	Medium (HO process)	Low / No
Signalling Load in J1 (iSC-RANaaS)	Medium (CSI information)	Medium (CSI information and HO process)
Processing Gains	Low	Low
Preferred Deployment	High small cell density	High small cell density
Potential standardization impacts	No impact	No impact
C-Plane/U-Plane considerations	Requires C-plane data	Requires C-plane data
veNB impacts	Selection algorithm performed at RANaaS, (re)selection performed as a handover in the involved iSCs.	Selection algorithm performed at RANaaS, (re)selection performed as a handover in the involved iSCs and RANaaS.
Impacts/requirements on implementation	Low	Low

5.5.2 Inter-cell RRM

The Radio Resource Management (RRM) encapsulates several functions, i.e. Radio Bearer Control, Radio Admission Control, Connection Mobility Control, Dynamic allocation of resources to UEs (in both uplink and downlink) and Inter-cell RRM. The latter is closely coupled with dynamic inter-cell interference management, and more specifically to coordination (ICIC / eICIC) function, as defined in 3GPP Rel 8-10.

Inter-cell interference coordination has the task to manage radio resources such that inter-cell interference is kept under control. ICIC is inherently a multi-cell RRM function that needs to take into account the resource usage status and traffic load situation of multiple cells. The preferred ICIC method may be different in the uplink and downlink.

Description of Functionality

In E-UTRAN, dynamic inter-cell interference management is supported based on message exchanged between neighbour cells over X2 interface [118].

For the downlink interference case this involves the employment by each cell of the relative narrowband transmit power (RNTP) for DL transmissions [118], in order to inform the other neighbouring cells whether to set the transmit power below a certain threshold value or not.

On the other hand, taking into account uplink interference, an Overload Indicator (OI) can be used during UL transmissions. Moreover, interference and power measurements for each Resource block are exchanged between different cells. In this direction, a High Interference Indicator (HII) can be used, which allows one of the cells to inform the neighbouring cells of an uplink transmission utilizing one of its cell-edge indicating to other neighbours that their cell-edge users experience high interference.

For heterogeneous interference scenarios (macro, femto / pico), 3GPP Rel-10 introduced enhanced Inter-cell interference coordination (eICIC) techniques under three major categories that lie in: Time, Frequency and Power domain. In time domain, the aggressor eNBs set almost blank sub-frame (ABSF), where only minimal control signals are transmitted, and inform the eNB with victim UE's of the ABSF pattern via the X2 interface. Following, in frequency domain, the control and reference signals are scheduled in reduced bandwidth, so that the signals of different cells are ensured to be orthogonal to one another. Finally, power domain involves the application of different power control techniques at small cells.

General challenges

In dense small cell deployment one key challenge is the high signalling load required in X2 (J2 in iJOIN) between small cells (multiple strong interferers and frequent users' handovers). In particular, small cells are unlikely to be connected directly to the core network and thus only limited small cells' backhaul signalling for interference coordination is possible. In this context, centralization could provide high processing gain and holistic/systematic interference mitigation.

Moreover, very low latency backhaul is required between iSCs and iSC-RANaaS in J2, J1. Here, a feasible solution could be the central controller to be locally deployed to avoid large delays.

Finally, the self-organizing capability of small cells might also require continuous sensing and monitoring of the radio environment in order to dynamically and adaptively mitigate interference.

Options for functional split

Split option A

In this scenario, Inter-cell RRM for UL/DL is performed in iSC (with the optional aid of RANaaS). More specifically, for the downlink interference case, the RNTP is exchanged in J2, informing the other neighbouring iSCs whether to set the transmit power below a certain threshold value or not. Following, RANaaS resolves resource conflicts between iSCs when they occur (iSC-RANaaS in J1).

For the uplink interference case, the overload indicator, interference and power measurements for each RB would get exchanged in J2 between different iSCs. Moreover, the high interference indicator is used by each iSC so as to notify the neighboring iSCs of an uplink transmission utilizing one of its cell-edge prohibiting other iSCs from scheduling their own cell-edge. Here, RANaaS role is to resolve resource conflicts between iSCs when they occur (iSC-RANaaS in J1)

Split option B

In this option, Inter-cell RRM for UL/DL is performed in RANaaS. For the downlink case CQI feedback is sent by each iSC over J1, informing RANaaS about all the users' channel conditions. Thereafter, RANaaS processes all this information and dynamically allocates RBs to iSCs / users. On the other hand, for the uplink case, the overload indicator, interference and power measurements for each RB would be sent to RANaaS in J1 by each iSC. Following, RANaaS will send the resource allocation decisions in J1 to all the corresponding iSCs.

Summary

The main advantages of the centralization of Inter-cell RRM for dense small cells is the more holistic / systematic interference mitigation / avoidance which can lead to higher overall spectral efficiency, and the high processing gains using the cloud processing capabilities.

On the other hand, the centralization poses some issues regarding the backhaul network between small cells and small cells – RANaaS. In particular, the signalling overhead and complexity increases with the number of iSCs /users in the system comprising of small cells. Moreover, low latency backhaul is highly required.

Below, Table 5-16 we summarize the requirements in terms of backhaul and processing needs for the aforementioned options.

Table 5-16: Summary of pros/ cons for the Inter-cell RRM options

	Option A Inter-cell RRM in iSC (conflict resolution in RANaaS)	Option B Inter-cell RRM in RANaaS
Computational needs in iSC	High	Low
Computational needs in RANaaS	Low	High
Signalling Load in J2 (iSC-iSC)	High	Low / No
Signalling Load in J1 (iSC-RANaaS)	Low	High
Processing Gains	Low	Very High
Preferred Deployment	Medium / Low small cell density	High user/ small cell density
Potential standardization impacts	TBD	TBD
C-Plane/U-Plane considerations	Requires C-plane data	Requires C-plane data
veNB impacts	FFS (probably none or only minor)	FFS (probably none or only minor)
Impacts/requirements on implementation	FFS	FFS

5.5.3 Segmentation/Reassembly

Description of Functionality

The segmentation function is located in the Radio Link Control (RLC) layer at the transmitter and the reassembly function is located in the RLC layer at the receiver. The RLC layer is, together with the PDCP layer, responsible for the link reliability functionality such as re-transmissions and re-ordering. There are three modes used in 3GPP LTE: Transparent Mode (no actions applied within RLC), Unacknowledged Mode (no retransmissions performed; used for voice/interactive video), and Acknowledged Mode (re-transmissions; used for TCP traffic etc.).

On transmitter side, the PDCP layer adds serial numbers (SNs) and performs cyphering as well as robust header compression. The RLC layer then receives these packets as SDUs from the PDCP layer and queues them in its transmission queue. SDUs are then segmented in order to fit the RLC PDU size which is given by the Medium Access Control (MAC) layer based on available physical resources and chosen MCS. In addition, the RLC layer needs to handle required re-transmissions of previously sent but not correctly decoded data packets. Afterwards, the RLC layer adds a header with an SN, framing information (how are SDUs split), and a length indicator to each SDU which is then handed over as PDU to the MAC layer.

On the receiver side, the RLC layer receives incoming packets and buffers them in order to handle duplicates and out-of-order packets caused by Hybrid ARQ re-transmissions (up to eight HARQ processes are allowed). The RLC layer unpacks PDUs and then re-assembles SDUs. If parts of an SDU are missing or not delivered after a time period *t-Reordering*, SDUs are dropped and reported through a status report which leads to a RLC re-transmission. Afterwards, PDCP checks for out-of-order packets, e.g. during handover when packets may be forwarded through the X2 interface from the source base-station, packets are re-ordered.

General challenges

The first challenge is errors on the backhaul and their impact on the 3GPP performance. One possibility is to handle those errors using standard mechanisms on the RLC layer even though this implies unnecessary overhead on the wireless interface between user terminal and base station. An alternative solution is to re-transmit on the backhaul link (in Acknowledged Mode) in order to reduce both delay and overhead on the wireless link.

The second challenge is jitter on the backhaul link which adds up to the end-to-end jitter. Hence, the timers maintained by the base station may need to be adjusted in order to compensate the increased jitter. In particular, the base station needs an interface to the network controller in order to receive an estimate of the jitter on the backhaul link.

Finally, the MAC layer defines the size of RLC PDUs depending on channel conditions and available resources. If the latency on the backhaul link is low, there is no significant impact. However, in the case of high backhaul latency, the actual preferred link adaptation and therefore transport block size of the MAC layer may be outdated at the point in time when RLC prepares the PDU for the MAC layer. This can lead to an increased outage and re-transmissions due to imperfect link adaptation. Besides HARQ, also a more conservative choice of MCS may solve the problem but at the cost of a lower throughput.

Options for functional split

Split option A

In the case of option A, the functional split is applied between MAC and RLC layer. In downlink, the RLC sends RLC SDUs over J1 to MAC located in iSC and in the uplink MAC sends MAC SDUs over J1 to RLC located in RANaaS.

This implies that, in the case of downlink, MAC needs to maintain a buffer in order to cope with jitter on the J1 link as well as caused by different computation time per PDU. It further needs to be resilient regarding potential packet drops on J1, which is a general requirement. In the uplink, the RLC layer needs a buffer too in order to cope with the jitter on the J1 link.

The interface towards veNB controller function needs to allow for exchanging information on the number of bytes that are requested and delivered, it needs to provide sufficient link reliability and in-order delivery on the J1 interface, and it needs to offer sufficient bandwidth to carry the additional control information, which should be negligible.

Split option B

In the case of option B, the functional split is applied between RLC and PDCP layer or sub-functions within PDCP layer. In the downlink, the PDCP layer sends RLC SDUs over the J1 interface to the RLC layer in the iSC, while in the uplink, the RLC layer sends RLC SDUs over the J1 interface to the PDCP layer. However, the functional split may also be different for uplink and downlink (asymmetric functional split). Accordingly, in the downlink the RLC layer needs to maintain a buffer for incoming RLC SDUs. This buffer already exists in standard implementations as described above and therefore no major implementation impact is expected. The requirements of this option are similar to option A except that no interface for reporting the required number of bytes is required.

Summary

In general, a centralization of RLC and PDCP layer allows for exploiting processing gains due to balancing of computational load. Furthermore, protocols and their implementation may change more often than PHY layer implementations. A centralized implementation in the RANaaS allows for fast updates and for field-test before updates are taken into operation. Furthermore, operators may run different RLC versions in parallel in order to support legacy terminals but also benefit from new releases. Finally, a centralized RLC and PDCP may be co-located with a centralized scheduler which could benefit from side-information.

However, RLC and PDCP layer processing are not as computationally expensive compared to PHY layer. Therefore, the processing gain due to centralization will be not significant. Furthermore, it may not offer throughput improvements due to the centralization.

Table 5-17: Summary of pros/ cons for segmentation/reassembly.

	Option A	Option B
Computational needs in iSC	Low-Medium	Low-Medium
Computational needs in RANaaS		
Signalling Load in J2 (iSC-iSC)	No	No
Signalling Load in J1 (iSC-RANaaS)	Low	Low
Processing Gains	Low-Medium	Low-Medium
Preferred Deployment		
Potential standardization impacts	No	No
C-Plane/U-Plane considerations		
veNB impacts		
Impacts/requirements on implementation	Requirement of additional buffer at iSC	

6 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. Furthermore, when the RANaaS platform proposed in iJOIN is fully available, the promised centralized gains may lead to notable improvements with respect to the state of the art radio access technologies.

In this document, we have also investigated the integration of the WP3 enablers in the preliminary iJOIN logical architecture and the way to introduce the functional split concept in these innovative MAC/RRM solutions. In particular, for each of the new schemes developed, a particular care has been given to discuss the possible functional split options. Furthermore, the implementations of the cell selection, inter-cell RRM, and segmentation/reassembly in the functional split framework have been carefully investigated as the MAC protocols promise interesting gains. It is then shown how the optimization of the functional split allows for a better use of the available architecture and improved cross layer design.

In the following months, we aim to further investigate the proposed CT schemes and give a preliminary evaluation with respect to the current state of the art solutions.

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