Open Cell-less Network Architecture and Radio Resource Management for Future Wireless Communication Systems

by

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Abstract

In recent times, the immense growth of wireless traffic data generated from massive mobile devices, services, and applications results in an ever-increasing demand for huge bandwidth and very low latency, with the future networks going in the direction of achieving extreme system capacity and ultra reliable low latency communication (URLLC). Several consortia comprising major international mobile operators, infrastructure manufacturers, and academic institutions are working to develop and evolve the current generation of wireless communication systems, i.e., fifth generation (5G) towards a sixth generation (6G) to support improved data rates, reliability, and latency. Existing 5G networks are facing the latency challenges in a high-density and high-load scenario for an URLLC network which may coexist with enhanced mobile broadband (eMBB) services. At the same time, the evolution of mobile communications faces the important challenge of increased network power consumption. Thus, energy efficient solutions are expected to be deployed in the network in order to reduce power consumption while fulfilling user demands for various user densities. Moreover, the network architecture should be dynamic according to the new use cases and applications. Also, there are network migration challenges for the multi-architecture coexistence networks.

Recently, the open radio access network (O-RAN) alliance was formed to evolve RANs with its core principles being intelligence and openness. It aims to drive the mobile industry towards an ecosystem of innovative, multi-vendor, interoperable, and autonomous RAN, with reduced cost, improved performance and greater agility. However, this is not standardized yet and still lacks interoperability. On the other hand, the cell-less radio access network (RAN) was introduced to boost the system performance required for the new services. However, the concept of cell-less RAN is still under consideration from the deployment point of view with the legacy cellular networks. The virtualization, centralization and cooperative communication which enables the cell-less RAN can further benefit from O-RAN based architecture.

This thesis addresses the research challenges facing 5G and beyond networks towards 6G networks in regard to new architectures, spectral efficiency, latency, and energy efficiency. Different system models are stated according to the problem and several solution schemes are proposed and developed to overcome these challenges. This thesis contributes as follows. Firstly, the cell-less technology is proposed to be implemented through an Open RAN architecture, which could be supervised with the near real-time RAN intelligent controller (near-RT-RIC). The cooperation is enabled for intelligent and smart resource allocation for the entire RAN. Secondly, an efficient radio resource optimization mechanism is proposed for the cell-less architecture to improve the system capacity of the future 6G networks. Thirdly, an optimized and novel resource scheduling scheme is presented that reduces latency for the URLLC users in an efficient resource utilization manner to support scenarios with high user density. At the same time, this radio resource management (RRM) scheme, while minimizing the latency, also overcomes another important challenge of eMBB users, namely the throughput of those who coexist in such a highly loaded scenario with URLLC users. Fourthly, a novel energy-efficiency enhancement scheme, i.e., $(3 \times E)$ is designed to increase the transmission rate per energy unit, with stable performance within the cell-less RAN architecture. Our proposed $(3 \times E)$ scheme activates two-step sleep modes (i.e., certain phase and conditional phase) through the intelligent interference management for temporarily switching access points (APs) to sleep, optimizing the network energy efficiency (EE) in highly loaded scenarios, as well as in scenarios with lower load. Finally, a multi-architecture coexistence (MACO) network model is proposed to enable inter-connection of different architectures through coexistence and cooperation logical switches in order to enable smooth deployment of a cell-less architecture within the legacy networks.

The research presented in this thesis therefore contributes new knowledge in the cell-less RAN architecture domain of the future generation wireless networks and makes important contributions to this field by investigating different system models and proposing solutions to significant issues.

Keywords Fifth generation (5G) and beyond, Sixth generation (6G), Radio access network (RAN), Open radio access network (O-RAN), Energy efficiency (EE), Base station (BS), Access point (AP), Radio resource management (RRM), Sleep mode approach, Cell-less network, Schedulers, Multi-architecture coexistence (MACO) network, Ultra reliable low latency communication (URLLC).

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Dedicated to all the people in the world
who stand for justice and against violence

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List of Abbreviations

3G third generation

3GPP 3rd generation partnership project

4G fourth generation

5G fifth generation

6G sixth generation

AE antenna element

AP access point

AR augmented reality

B5G 5G and beyond

BBU baseband unit

BLER block error rate

BS base station

Capex capital expenditure

CCDF complementary cumulative distribution function

CCI co-channel interference

CDF cumulative distribution function

CoMP coordinated multi point

COTS commercial-off-the-shelf

CQI channel quality indicator

C-RAN cloud/centralized RAN

CSI channel state information

CSI-RS channel state information reference signal

CU centralized unit

CUPS control and user plane separation

DC dual connectivity

D-RAN distributed RAN

DU distributed unit

EE energy efficiency

EEE energy efficiency enhancement

eMBB enhanced mobile broadband

FD frequency domain (scheduler)

GA genetic algorithm

HARQ hybrid automatic repeat request

HetNets heterogeneous networks

IAR inter architecture roaming

ICI inter-cell interference

ICR interference contribution ratio

KPI key performance indicator

MACO multi-architecture coexistence

MANO management and network orchestration

MCS modulation and coding scheme

MGA modified genetic algorithm

MIESM mutual information effective SINR mapping

MIMO multiple-input-multiple-output

mMIMO massive multiple-input-multiple-output

mMTC massive machine type communication

msec millisecond

NACK negative acknowledgement

near-RT-RIC near real time RAN intelligent controller

NG-RAN next/new generation RAN

NR new radio

OFC OpenFlow controller

OFDM orthogonal frequency division multiplexing

OFDMA orthogonal frequency division multiplexing Access

Opex operational expenditure

O-RAN open radio access network

PDSCH physical downlink shared channel

QOS quality of services

RAN radio access network

RANC RAN controller

RAT radio access technology

RB resource block

RE resource element

RIC RAN intelligent controller

RR round robin

RRH remote radio head

RRM radio resource management

RRU remote radio unit

RSRP reference signal received power

RU radio unit

SDN software defined networking

SINR signal-to-interference-plus-noise ratio

SLA service level agreement

SMN smart metering network

SMO service management and orchestration

SOTA state-of-the-art

TCO total cost of ownership

TD time domain (scheduler)

TRP Tx/Rx point

TTI transmission time interval

UDN ultra dense network

UE user equipment

VNF vitual network functions

VR virtual reality

V-RAN virtualized RAN

URLLC ultra reliable low latency communication

PUBLISHED AND SUBMITTED CONTENT

- **Farinaz Kooshki**, Ana García Armada, Md Munjure Mowla, Adam Flizikowski and Slawomir Pietrzyk, "Energy-Efficient Sleep Mode Schemes for Cell-less RAN in 5G and beyond 5G Networks", *IEEE Access*, vol. 11, pp. 1432-1444, 2023. DOI: 10.1109/ACCESS.2022.3233430. [Published].

  This work has been wholly included in the thesis, in chapters 2, and 6. It proposes an energy-efficient RRM scheme in the cell-less RAN architecture. The material from this source included in this thesis is not singled out with typographic means and references.

- **Farinaz Kooshki**, Md Munjure Mowla, and Adam Flizikowski, "Multi-Architecture COexistence Enabling Network Framework for 5G and Beyond Mobile Systems", *IEEE Conference on Standards for Communications and Networking (CSCN 2022)*, Greece, [Published].

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- **Farinaz Kooshki**, Ana García Armada, Md Munjure Mowla, and Adam Flizikowski, "Radio Resource Management Scheme for URLLC and eMBB Coexistence in Cell-less Radio Access Network", *IEEE Access*, [Submitted for publication].

  This work has been wholly included in the thesis, in chapters 2, and 5. It proposes an enhanced RRM scheme in the cell-less RAN with a URLLC and eMBB coexistence scenario. The material from this source included in this thesis is not singled out with typographic means and references.

- Md Arifur Rahman, **Farinaz Kooshki**, Suvidha Mhatre, Slawomir Pietrzyk, and Adam Flizikowski, "Cooperative radio resource allocation in a wireless communication network and methods for use therewith", US Patent App. 17/456,193, Jun. 2022. Available: https://patents.google.com/patent/US11502793B2. [Has been granted].

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- Slawomir Pietrzyk, Md Munjure Mowla, Adam Flizikowski, **Farinaz Kooshki**, Adam Girycki, and Jakub Piotr Kocot, "Cooperative radio resource scheduling in a wireless communication network and methods for use therewith", US Patent App. 17/645,917, Jun. 2022. Available: https://patents.google.com/patent/US20220210794A1. [Under examination].

  This work has been partly included in the thesis, in chapters 2, and 3. The partial contribution in this work (which has been included in the thesis) proposes a topology formation strategy to design a cell-less network in an Open RAN framework. The material from this source included in this thesis is not singled out with typographic means and references.

- **Farinaz Kooshki**, Ana García Armada, Md Munjure Mowla, Adam Flizikowski, and Slawomir Pietrzyk, "Energy efficient cell-less radio network and methods for use therewith", US Patent App. 63/379,524, Oct. 2022, [Provisional].

  This work has been partly included in the thesis, in chapters 2, and 6. It proposes an energy-efficient cell-less radio network and methods. The material from this source included in this thesis is not singled out with typographic means and references.

Chapter 1

Introduction

The fifth generation (5G) and beyond communication networks are supposed to accommodate the ever-increasing user demands of better experience and more flexible networks with regards to different use cases as well as the more stable connectivity. The 5G and beyond networks are predicted to deploy new use cases including intelligent communications, smart transport, green communication, virtual reality, remote driving, converged heterogeneous networks (HetNets) connectivity and etc as a product of expanding networks from people to things connectivity.

However, to achieve successful deployment of 5G and beyond networks, there is a huge challenge when the networks should be densified significantly to overcome these extremely increasing demands. The challenge will go across the new well-matched infrastructure and architectural design, system integration, energy efficiency, programmability of such massive communications and maintaining its stability, and control over the combination of many advanced integrating technologies. On the other hand, inter-cell interference increased as a result of small cells ultra dense network (UDN). The competition for the available limited resources has increased among end users. Therefore, stable communication network availability requires a delicate network provisioning. The industry and academia start to dig into shaping the vision toward sixth generation (6G) networks, as it is predicted that by end of 2025s, 5G will not be capable to overcome the significant needs of the extreme demands from a fully digitalized ecosystem [1]. From the evaluation of the network performance for use cases and providing services, beyond networks should offer highly efficient performance in terms of different key indicators such as rate, latency, density of connection, energy efficiency and etc [2]. On the other hand, the existing cellular network was intended to provide service for a large geographical area. However, within today's ultra dense networks, cellular networks are no longer considered as a promising solution to resolve the aforementioned challenges ensuring 5G and beyond target key performance indicators (KPIs). In addition, conventional architectures are no longer able to deal with the complexity of network evolution. Hence, there is a strong need to revisit the existing methodologies and recap the performance enhancement opportunities.

To that end, new enabling technologies are needed to push the network forward. Each of emerging 5G and beyond pillars' technologies can be under different categories including infra-structure and architecture, transmission technologies, interference management, energy efficiency techniques, spectrum management and carrier aggregation. One of the potential solutions among all is *cell-less* radio access network (RAN) as a new network paradigm which we explore in this thesis. In cell-less design, the RAN is transparent from the users' point of view and users treat entire radio resources as a unique pool, where the cell boundaries are removed.

1.1 Motivation

Recently, there have been proposed solutions including massive multiple-input multiple-output (mMIMO), coordinated multi point transmission (CoMP), network MIMO, dual connectivity and others to overcome UDN limitations such as inter-cell interference, ping pong handover, network congestion and convergence problems. However, they were not resolving all the issues like signaling overheads, computational complexity, or practical gain lower than the theoretical. Cell-less concept has opened a new research line and facilitates 5G and beyond networks with a potentially enhanced network behavior. In legacy networks, each user is associating with a particular cell through a competitive scheduling with another cell. Whereas, shifting the design to the cell-less RAN, users will no more suffer from the interference received from the other cells as a result of a cooperative scheduling approach. The new design will not only overcome the existing obstacles, but also will provide users of the network with higher performance regarding the target key performance indicators (KPIs) thanks to its innovative enabled techniques. The performance optimization could be on any of 5G service types among enhanced mobile broadband (eMBB), ultra-reliable and low-latency communications (URLLC) and massive machine type communications (mMTC) from the predefined configurations. The setup will cover a variety of objective functions such as throughput, energy efficiency, latency etc.

Cell-less network is a novel evolving technology as a combination of concepts including softwarization, virtualization, centralization, network MIMO, and cooperative radio resource management (RRM). For the network wide cooperation there is a need for a central controller. There are existing attempts utilizing centralized processing for network cooperation built on techniques such as centralized/cloud RAN (C-RAN), software defined networking (SDN) based controller and others [3], [4]. However, these techniques limit the potential capabilities of cell-less networking because of not being fully scalable and making the communication network face vendor lock-in issues for the deployment of new technologies integration. Therefore, the research interest has increased for a scalable network through decentralizing the processing [5]. However, the industry is showing more interest to go further for a practically and feasibly implementable architecture which not only supports disaggregating networks, but also the vision for a new RAN architecture shaped as open RAN to eliminate vendor lock-in issues and bring more vendors to shape an open ecosystem by opening the internal RAN interfaces. Open RAN is promoted by the O-RAN Alliance, which publishes the specifications related to the new RAN. It extended the disaggregated NG-RAN defined by 3rd generation partnership project (3GPP) [6] by introducing the RAN intelligent controller (RIC). Through the introduced RIC implementation, xAPPs are enabled on top of RAN to enhance the scalable network performance for the end users.

In that respect, it seems important to explore the effective RRM techniques for cell-less networks. Despite many techniques being proposed, they are still not achieving the maximum impact of potential efficient resource scheduling techniques in a cooperative manner within a cell-less open RAN network. This is a new wave of future RAN in an open ecosystem where further research needs to be carried out. This thesis aims to fill some of these remaining gaps, in addition to approaching the question of how the migration path toward an ideal cell-less open network should be feasible for operators and all other players of the mobile communication networks.

1.2 Aim of the thesis

The principal aim of this thesis is to present different models, techniques, schemes, and solutions of the new cell-less radio access network paradigm for the next generation wireless networks. More specifically, this thesis introduces new ideas to achieve the full diverse benefits of the cell-less RAN by investigating and introducing the cell-less architecture in the Open RAN framework, efficient RRM for system capacity maximization and latency minimization, energy efficiency, and multi-architecture coexistence network scenarios. The main aim is achieved by pursuing the following objectives:

- To investigate a cell-less networking approach in the Open RAN framework to avail more networking benefits.
- To design an efficient RRM for the cell-less architecture to enhance the system capacity.
- To develop an enhanced RRM scheme for the cell-less architecture to minimize latency in the URLLC and eMBB coexistence network scenarios.
- To design an energy efficient enhancement solution for the cell-less RAN architecture.
- To investigate the multi-architecture coexistence network scenarios, i.e., cell-less and cellular.

1.3 Contribution of the thesis

The contributions of this thesis come from analyzing the existing network challenges regarding design, RRM, and energy efficiency for the cell-less radio access network in the future generation wireless network, and then developing new schemes and techniques to overcome these challenges. In brief, the novelty of this work is found as follows: (i) a novel cell-less design approach is presented in the Open RAN framework; (ii) an efficient RRM algorithm is developed for cell-less RAN to maximize capacity; (iii) an efficient RRM scheme is proposed to optimize the latency-capacity performance in URLLC and eMBB coexistence network scenarios; (iv) a green solution for a cell-less RAN architecture is developed to improve the energy efficiency of the network; and (v) a multi-architecture coexistence network is designed with suitable switching modes for smooth transition. The major contributions of this research work described in this thesis are as follows:

- The first contribution of this thesis is to design a cell-less architecture in the Open RAN framework in order to improve the network performance by enabling virtualization, centralization, and cooperative communication which could not only open the network, but also open the way toward efficient optimization functionalities. The cell-less topology formation strategy is proposed within the Open RAN structure. The signaling flow to enable the network establishment for the proposed cell-less communication is designed to support users attaching to the network and being considered for the scheduling procedure.

- The second contribution of this thesis is to propose an efficient RRM algorithm for the cell-less RAN to improve the system capacity performance. The mathematical model, algorithm, and performance results from the associated simulations are also outlined. In this work, the approach of cell-less RAN is validated by considering the assumption of mitigating the network level interference introduced by the utilization of the same resources of the underlying RUs. The potential benefits of the proposed approach and its RRM strategies over the legacy cellular RAN approach are highlighted through simulation results. In addition, the effect of user density of the proposed algorithm with the legacy networks are analyzed and compared in terms of system capacity performance enhancement for a different scale of network setup in several deployment environments. The simulation results illustrate that the proposed cell-less NG-RAN design provides significant system capacity improvement over the legacy cellular solutions.

- The third contribution of this thesis is to introduce an enhanced RRM scheme to minimize the latency of URLLC devices in a coexistence network scenario with eMBB for a cell-less RAN architecture. This scheme improves the latency performance by an efficient scheduling that considers the number of resources required for delivery of URLLC packets. In this work, a time domain (TD) scheduler is developed by proposing a ranking algorithm from a radio unit (RU) perspective which will support the efficiency of scheduling in terms of resource consumption in large scale networks. Also, a frequency domain (FD) scheduling algorithm is introduced by using the interference contribution ratio (ICR)-based approaches to avoid the eMBB users throughput degradation that can be caused by competition of newly admitted users to the network with existing ones. The proposed scheme has a 29% latency improvement for URLLC and 90% signal-to-interference-plus-noise ratio (SINR) improvement for eMBB users as compared with conventional scheduling policies.

- The fourth contribution of this thesis is to develop an energy-efficient scheme in the cell-less architecture towards its practical deployment in 5G and beyond networks. This includes a two-step sleep mode selection (i.e., certain phase and conditional phase) with an intelligent controller that dynamically updates the user and RU association and switches the unnecessary RUs to sleep. The proposed approach controls the interference at dense environments in a way that transmission is performed only if it is beneficial for the increment of the network EE. Meanwhile, the proposed ($3 \times E$) scheme employs conditional sleeping criteria with traffic load-based customization in addition to an interference consideration to assure maintaining efficient power saving for networks with various user densities. Simulation results show that the network energy efficiency (EE) is improved up to 30% compared to the reference algorithm and up to 60% with respect to the baseline algorithm in which all APs are active all the time.

- The fifth contribution of this thesis is to propose a multi-architecture coexistence (MACO) model to enable interconnection of two different architectures, i.e., cellular and cell-less. This will allow the legacy architecture transition to the cell-less architecture, where they perform cooperative communication toward beyond 5G network. Moreover, the switching modes i.e., coexistence switch and cooperation switch in the MACO models are presented which could be used for real-time and near real-time applications.

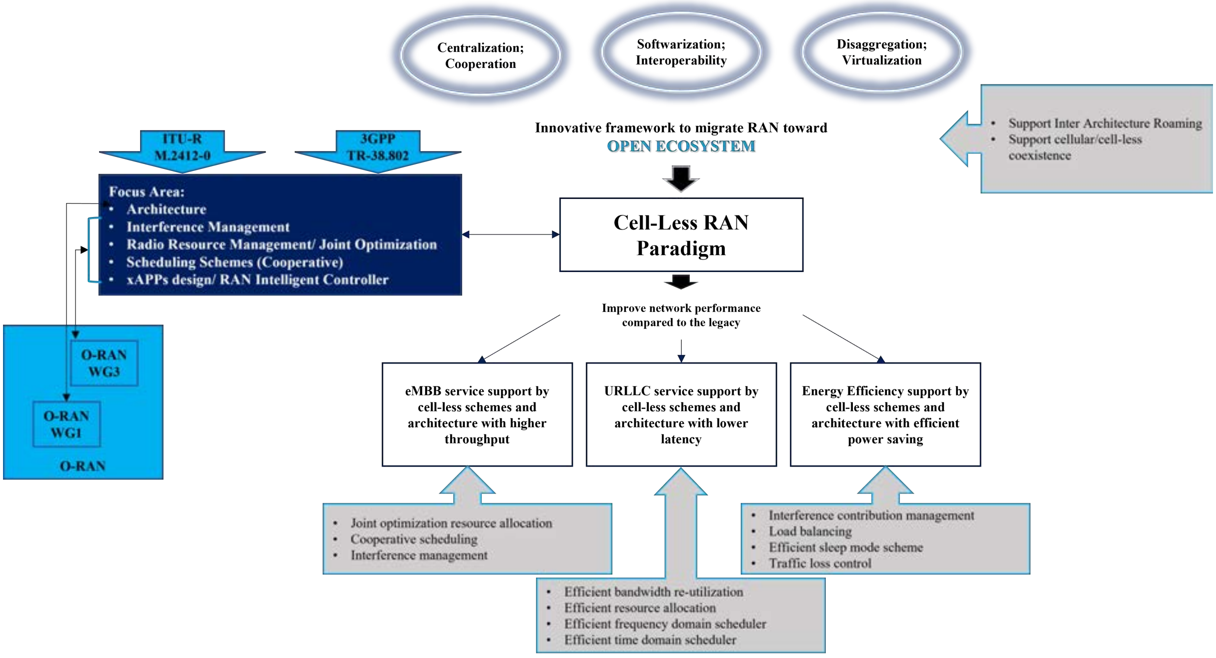


Figure 1.1: Research objectives and focused areas.

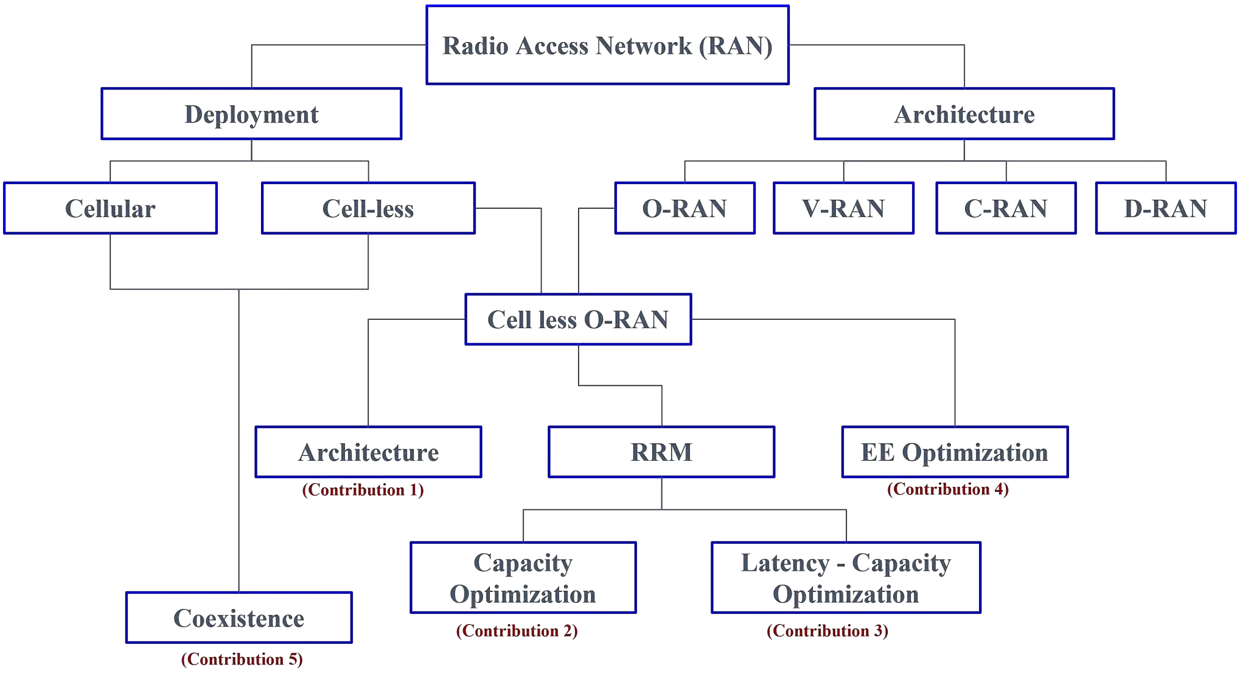


Figure 1.2: Research contribution.

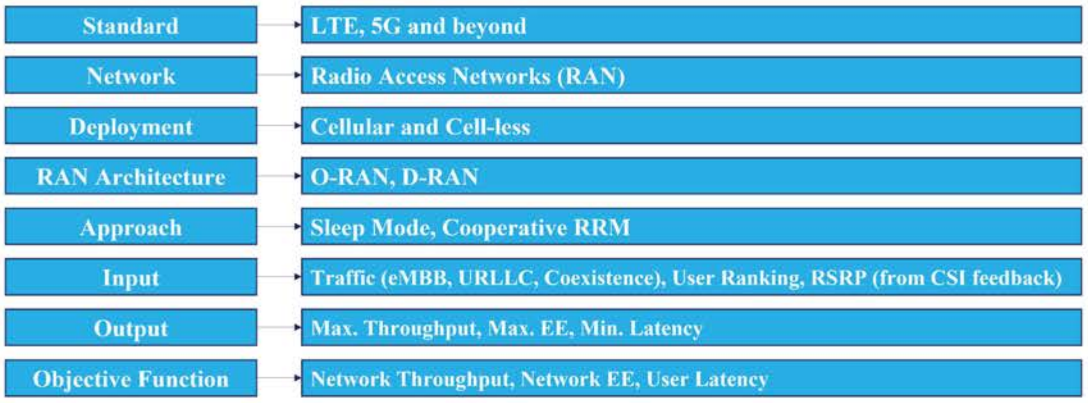


Figure 1.3: Methodological framework for this thesis.

1.4 Organization of the thesis

This thesis is organized as follows:

- Chapter 1 introduces the current and future trends of mobile communication traffic demands and discusses the network architecture of the next generation of wireless communication systems, i.e., 5G and beyond. This chapter also discusses the research motivation and contributions of the thesis.

- Chapter 2 presents the technical background of 5G and beyond systems. This includes the RAN and its evolution towards next generation wireless communication networks. A general system model is shown to outline the specific challenges considered for this thesis. The related state-of-the-art solutions are discussed and the research gaps are highlighted. Finally this chapter identifies the research questions underpinning this thesis.

- Chapter 3 shows the cell-less RAN design approaches in the Open RAN framework. This chapter describes the proposed architecture with corresponding elements, interfaces and signalling flows to establish the cell-less network. This research is part of the work in the patent [7].

- Chapter 4 proposes an efficient RRM scheme for the cell-less RAN to boost the system capacity for the end users. This chapter provides an optimization model with a modified Genetic algorithm based solution to enhance system capacity in the cell-less architecture for future wireless communication networks. This research is submitted to IEEE Networking Letters [8] and now under-review. It has also contributed in the granted patent [9].

- Chapter 5 introduces an efficient RRM scheme for minimizing the latency of URLLC devices in a coexistence network scenario with eMBB for a cell-less RAN architecture. This chapter includes an optimization model with two novel developed schedulers (TD and FD) to enhance the system performance. This work is submitted to IEEE Access [10] and now under-review.
- Chapter 6 investigates the green aspects of the cell-less architecture in 5G and beyond networks. An optimization model is formulated with the aim of maximization of energy efficiency where a novel energy-efficiency enhancement scheme, i.e., $(3\times E)$ is proposed to increase the transmission rate per energy unit, with stable performance within the cell-less RAN architecture. This research is published in IEEE Access [11]. The corresponding patent of the work is provisioned in [12].
- Chapter 7 explores the multi-architecture coexistence network scenarios, i.e., cellular and cell-less for the future generation networks. This chapter includes the switching mode mechanisms, i.e., coexistence and cooperation for the new use cases and applications. This work [13] is published in IEEE Conference on Standards for Communication and Networking (IEEE CSCN), Thessaloniki, Greece, Nov. 2022.

Chapter 2

Background and literature review

2.1 Beyond 5G

The 5G network commercialization has been started across the world promoting an improved performance which makes space for the life cycle of the holding services, put on standby due to 4G limitations, back in the game, along with some innovative ideas [14]. The various demands are classified in three pillars of eMBB, URLLC and mMTC. The giant growth of mobile traffic by 2030 will strain the 5G network. Global mobile traffic will grow to more than 5036 EB monthly in 2030 [15] as it is shown in Fig. 2.1. Hence, academia and industry are shifting their attention to beyond 5G or 6G networks to fulfill the future demands of the 2030s.

The wireless communication network evolution toward 6G enables the architectural transformation to support on-demand service deployment and coordination of multi-network connectivity [16]. According to [17], it is expected that beyond 5G networks will have to deliver higher performance than it was required in 5G [18], as follows:

- The required capacity will be in the range of 10x the capacity requirements of 5G, up to 150 Tbps per square kilometer.
- Data rate will reach 10 Gbps.
- The latency communication will be less than 1 ms.
- It should support peak densities of up to 10 devices per square meter.

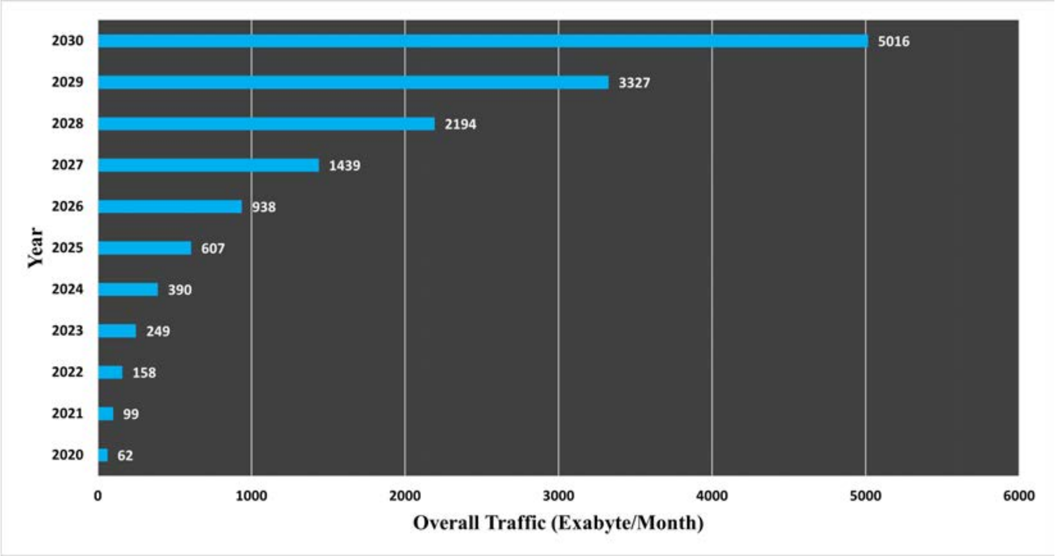


Figure 2.1: Estimations of global mobile traffic in 2020-2030 according to ITU-R Report M.2370-0.

- The significant improvement in terms of energy efficiency will be expected.

Fig. 2.2 shows the quantitative comparison between 5G and beyond in terms of basic requirements in each network.

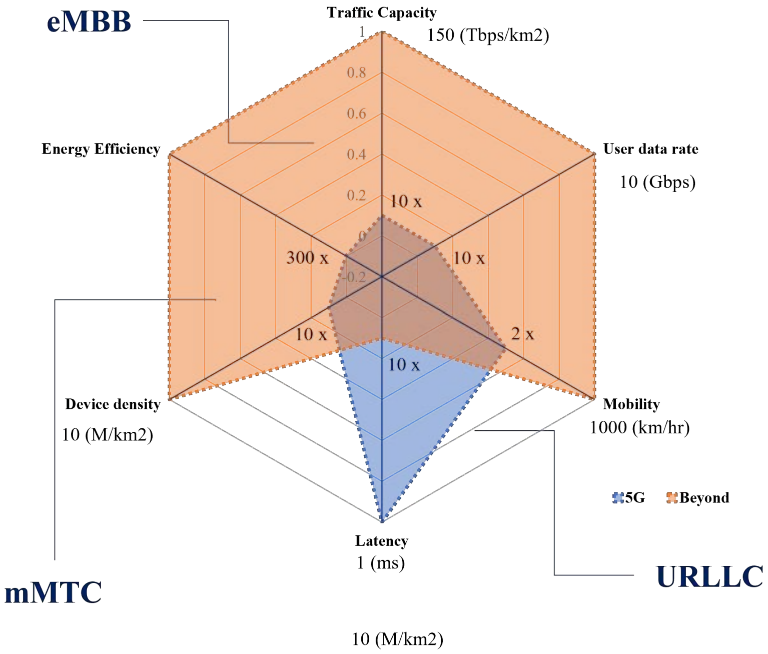


Figure 2.2: Quantitative comparison of requirements between the 5G and beyond network.

As it is shown in Fig. 2.2, each of the 5G scenarios will include a couple of these requirements. This thesis is focused on the use cases in different environments including indoor, urban micro and urban micro. Each scenario has different challenges that so far the research community and industry are dealing with. The focus area built on the novel cell-less concept could cover use cases that may be related to multiple angles of 5G triangle's scenarios (eMBB, URLLC, mMTC). This is because of their overlapped area in the corresponding KPIs' chart and the joint challenges that could be overcome by proper and efficient solutions. As a result, the new services and applications can be provided with higher performance for 5G and beyond networks within different use cases.

eMBB service is more focused on throughput optimization for users and network. However, along with network densification there are more obstacles the network will face to achieve the service requirements. Interference, limited scope of resources and high competition over available resources are among these challenges. On the other hand, URLLC service requires an ultra low latency and reliable communication to be provided for the end consumers. Whereas the demanding users increase, the probability of fulfilling such a requirement will be lower. Therefore, controlling the latency of the communication below 1 ms is a limiting factor for providing new services and applications in beyond 5G networks. In addition, the number of demanding expectations for such services with high performance is increasing day by day from people to things. It is hard to maintain the high quality connectivity for devices while providing services. It is worth highlighting the strong intention for an effective energy efficiency of the network all along its evolutionary path toward beyond 5G. New technologies are aiming to enable the network's target required KPIs. The parent pillars of these enabling technologies are highlighted in the chapter 1 as it is shown with an example of higher granularity in Fig. 2.3 [19].

Each technology provides different solutions to overcome network's identified challenges for meeting the target KPIs for a particular service. Moreover, a series of use cases explore 5G features of enabling technologies and shall develop solutions to enhance network performance. To that end, we concentrate on eMBB and URLLC services to provide solutions in response to the number of challenges. However, the high user density of future networks (approaching mMTC) as a potential showstopper has been considered as well in terms of its impact on achieving the service requirements.

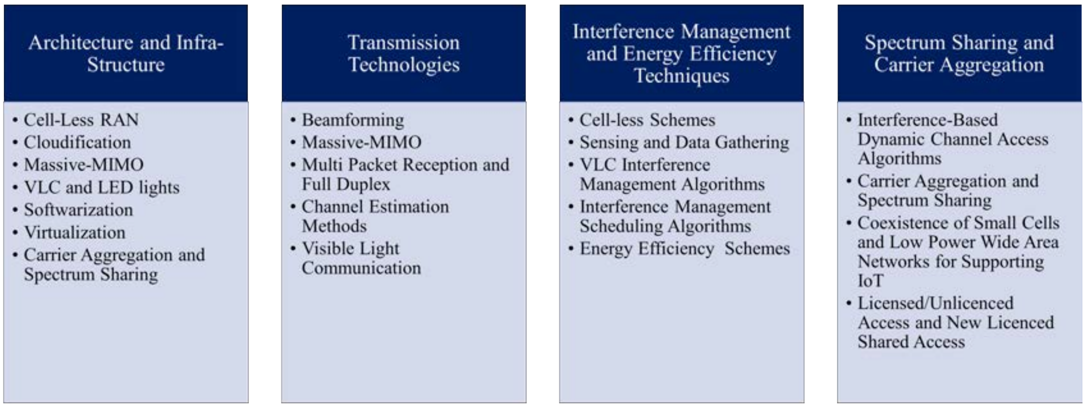


Figure 2.3: Enabling technologies for the 5G and beyond network.

Table 2.1: Summary of considered requirements within the thesis scope [(high importance, 5), (medium importance, 3) and (low importance, 1)].

KPI	eMBB	URLLC	eMBB - URLLC Coexistence	Energy Efficient eMBB
User experience data rate	5	1	3	5
Latency	1	5	5	1
Device density	3	5	5	3
Energy efficiency	1	1	1	5
Network traffic capacity	5	1	3	5

To that end, the following Table 2.1 summarizes the importance level of the main requirements foreseen at this thesis within the concentrated focused services. They are illustrated in Fig. 2.4.

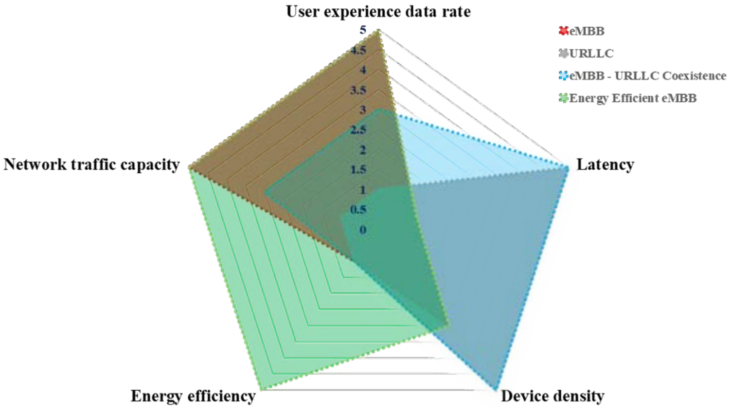


Figure 2.4: Polygon describing the foreseen requirements in the thesis.

2.2 Radio Access Networks (RANs)

The RAN is a collection of interlinked base stations that are connected to the core network and provide coverage in a specific area based on radio access technologies (RATs). Along with RAN evolution, the third Generation of mobile communication (3G) approached distributed RAN (D-RAN) systems by monolithic building blocks and communication taking place between nodes within the RAN. In traditional cellular RAN, the baseband units (BBUs) and multiple remote radio units (RRUs) are placed at the same integrated cellular site. BBU is responsible for performing network functions for the layers of the RAN protocol stack, and RRU for the transmission. In other words, a RAN provides radio access and assists to coordinate network resources across wireless devices within a telecommunication network. However, this approach can be costly since each BBU must be deployed co-located with each integrated radio site.

2.2.1 C-RAN

Cloud/centralized RAN (C-RAN) is an evolved RAN architecture for cellular networks that decouples BBUs from radio access units [20], [21]. The C-RAN utilizes cloud computing approaches where BBUs are grouped in a centralized pool, connected over optical fiber to remote radio heads (RRHs) in order to enable the real time collaborative network management. The BBUs' centralization will improve the coordination of RRHs in the neighboring cells for better resource management, which progresses the RAN into fourth generation (4G). In addition, thanks to the enhancement in BBU utilization, the capital expenditure (Capex) saving will be noticeable. The centralized BBU processing is required to have fronthaul links with high bandwidth and ultra low latency in C-RAN. However, the capacity of a link is usually limited and time-delayed in real-time applications.

2.2.2 Toward RAN Evolution: Disaggregation RAN, V-RAN, Open RAN

Both the D-RAN and C-RAN are based on hardware-based appliance implementation. The RAN evolved to deal with the challenges of a vendor lock-in issue, high total cost of ownership (TCO), energy consumption, etc. The RAN was approached by disaggregation in vertical and horizontal vectors [22] to transfer it into more standardized entities. This was in addition to the introduction to the cloud technology to enable scaling and automated deployments.

V-RAN The vertical disaggregation is between hardware and software through decoupling the virtual network functions (VNF) from purpose-built hardware. To that end, it will virtualize the centralized baseband processing (vBBU) into software running on the standard servers of commercial-off-the-shelf (COTS) servers instead of a special proprietary hardware. As a result, some advantages such as additional flexibility and lower cost of RAN deployment (with significant operational expenditure (Opex) saving) can be provided. However, inter-component interfaces may still be proprietary.

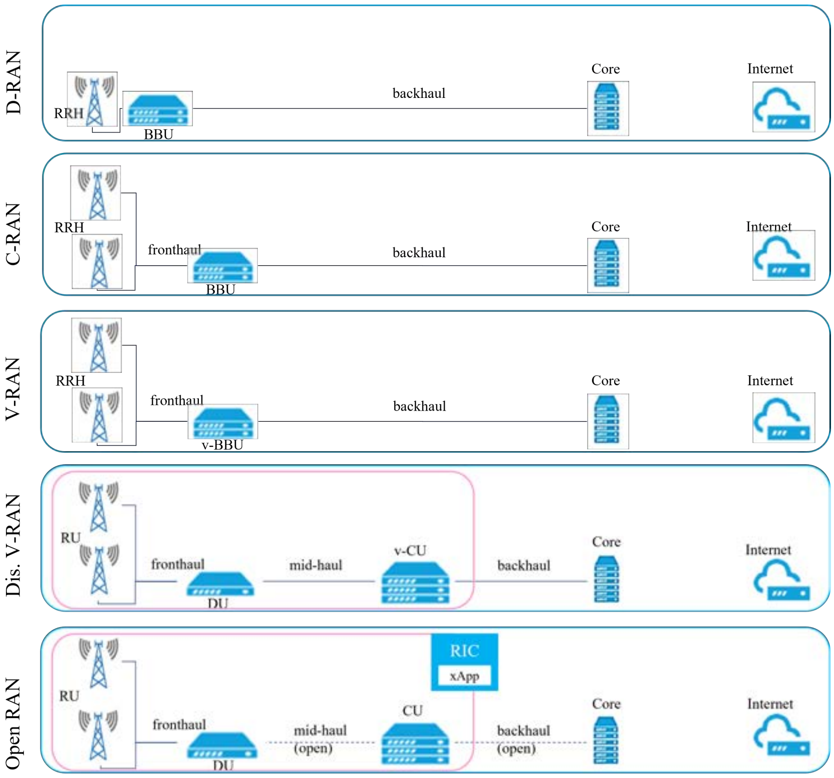


Figure 2.5: Evolution of the RAN Architecture.

Disaggregated V-RAN In the horizontal vector, a distribution in the deployment of RAN functions over the coverage is enabled which is defined by 3GPP [6], [23]. vBBU is disaggregated to centralized unit (CU) responsible for the packet processing and distributed unit (DU) responsible for the baseband processing functions. In addition to that, depending on the functional split of the protocol stack, radio unit (RU) as a representative for RRH will also be responsible for some of the radio functions with regards to the RAN coverage area. Backhaul connects core to CU, mid-haul link connects CU with DU and fronthaul connects DU with RU. Opening the interfaces among these disaggregated RAN elements will evolve RAN with the new concept of Open RAN. Fig. 2.5 shows the evolution of RAN architecture toward the Open RAN.

Open RAN Open RAN provides the diversity between vendors and multi-vendor interoperability which lets more players being engaged for deployment of the evolved programmable and automated RAN in the mobile telco industry. It will enable dynamic dimensioning thanks to the decoupled software and hardware and virtualization.

Recently, O-RAN was formed to extend the current RAN standards, which facilitate opening up the network interfaces in order to support disaggregation of the network [24] for future intelligent and interoperable RANs. Fig. 2.6 illustrates the O-RAN functional splitting within the disaggregated RAN infrastructure [25]. It includes the interfaces defined by O-RAN, in addition to management and network orchestration (MANO), which is responsible for management of the network. Open RAN provides a disaggregated strategy in line with control and user plane separation (CUPS), where DU and CU stacks are actually separate. However, the entities and features described in O-RAN are not scalable in number of services by design till now. Thus, in principle only limited services can be created in O-RAN (based on either CU and DU).

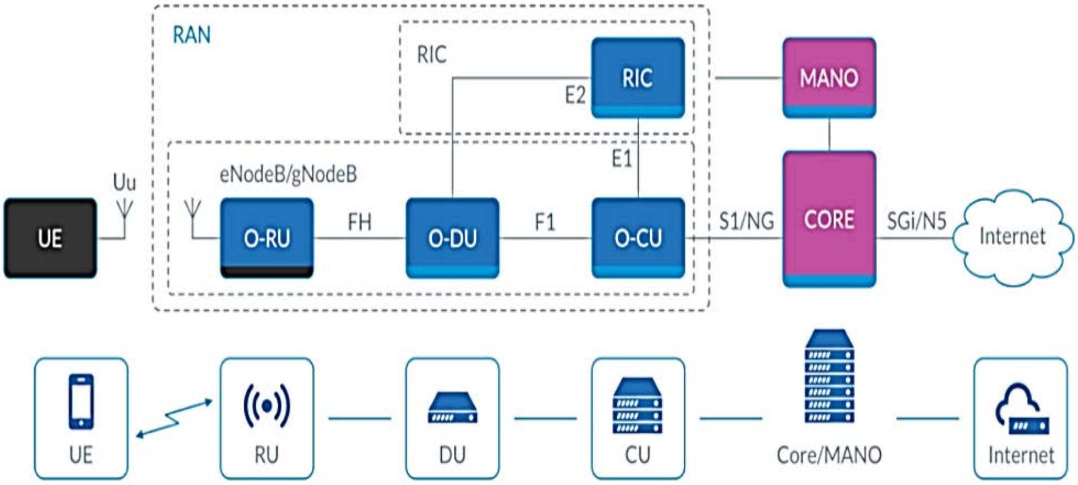


Figure 2.6: O-RAN functional splitting within disaggregated RAN infrastructure.

Open RAN architecture also includes the RAN intelligent controller (RIC) to enhance the RAN performance for the 5G and beyond services through software-defined controllability of RAN. The applications deploy in RIC, so-far called xAPPs, will facilitate the Open RAN with the improved RRM, load balancing, etc. This is whereas, the traditional RAN is not optimally managing the radio resources (because of the lack of associated intelligence on the coordination of the underlaid RAN).

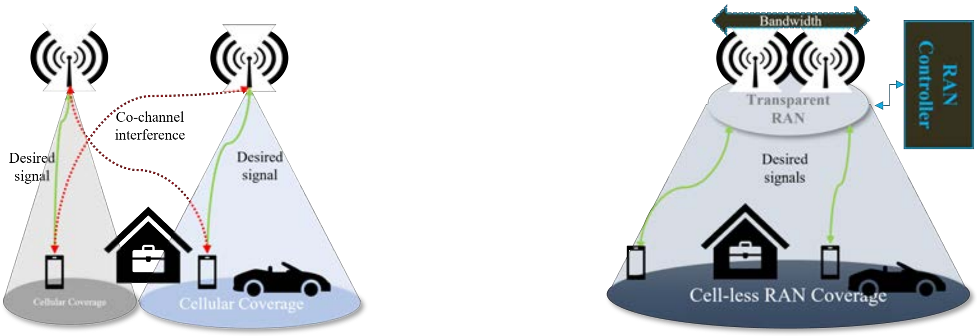
2.3 Radio Resource Management (RRM)

RRM is a system-level management over the radio resources including, time-frequency channels, co-channel interference, power, and any other radio transmission characteristics in wireless communication systems [26]. To utilize the finite available radio resources efficiently, different strategies and techniques are involved by RRM. These strategies will enable resources to adapt to the radio environment by dynamically adjusting users' access. Therefore, RRM plays a significant role in network performance. The new RRM functionalities have constantly been added to the architecture governing RRMs in RANs. However, RRM is involving an increasingly growing number of parameters along with RAN evolution [27]. With the new technologies being integrated in 5G and beyond networks, RRM is expected to reach an unprecedented complexity [28]. Therefore, such large-scale RRM problems are challenging for optimization, and utilize the resource scheduling strategy in competitive and cooperative approaches. The employed RRM approach will enable the RAN paradigm shift from cellular to cell-less.

Cooperative scheduling is a RRM method to utilize the potential interference as a useful signal. The higher system performance will be achieved through the interference management with the cooperative scheduling of the entire resources (time-frequency, power and RU). The cooperative scheduling is expected to outperform the cellular competitive ones as a result of managing the interference, which is a limiting factor for the performance enhancement.

2.4 Cell-less RAN Paradigm

The evolved networks are experiencing an open ecosystem enabled by O-RAN specifications and open software, when many players have come back to the game [29], consequently. New services and applications in 5G and beyond networks are requiring a smarter model of network. *Cell-less* is a new paradigm, which is proposed to achieve higher KPIs to the 5G and beyond ultra-dense networks. It breaks the obstacles from the cellular architecture down through both the convergence in different tiers of vertical and horizontal convergence in the cellular RANs [30]. In the cell-less architecture as a combination of centralization, softwarization, and virtualization, the cooperative RRM is considered to schedule the radio resources. RAN is transparent from users' point of view and they can dynamically communicate with one or any required number of access points (APs) if necessary. As it is shown in Fig. 2.7, the interference can be managed thanks to the change of the radio resource allocation paradigm from competitive to cooperative. An example of cooperative behavior is scheduling the resources in a policy-aware approach which means each AP knows about other APs scheduling decisions and will perform its scheduling based on the whole system scheduling status. When combined with the centralization of RAN, this concept makes independent "cells" (or independently managed cells) obsolete, hence the name "cell-less" RAN.



(a) cellular coverage

(b) cell-less coverage

Figure 2.7: RAN paradigm shift from cellular to cell-less

2.5 General system model

With regards to the 5G and beyond ultra-dense networks with the more exigent required KPIs for the new expected services and applications, we consider the cell-less RAN within the Open RAN architecture in this thesis. Fig. 2.8 shows a general system model focusing on the standards, deployment, approaches, and input-output. The UEs are connecting to the entire radio resources without being limited by the cell boundaries and they experience the RAN as a common unique zone. The disaggregated RAN inspired from the open RAN architecture - having disaggregated RU, DU, CU - is considered, where RU shows similar attributes to AP. The users associated with each RU may be served randomly or by any well-established scheduling technique. The central RAN controller (e.g., near-real-time RIC in O-RAN architecture) is supporting the coordination of RAN and the network information exchanging and storage. The UEs may be re-associated to different RUs at each transmission time interval (TTI). RIC is introduced by Open RAN architecture as a software-defined based component, which will optimize the RAN functions. Therefore, any player's application (i.e., xApp) could be onboard in the disaggregated virtualized Open RAN. The xAPPs is to enable services requiring fast loop control to provide a better experience of the network for the customers in a scalable manner with low TCO. In addition, the policy-based support to the near-real-time RIC will be provided by the running applications on the non-real-time RIC in the service management and orchestration (SMO).

As the cell-less RAN requires coordination among RUs for resource scheduling, RIC plays a significant role as a central controller. In this thesis, we focus on the multiple objective functions including (system capacity, throughput, EE and users' communication latency optimization) to improve network performance for the users. We aim to enhance the above mentioned KPIs for the eMBB and URLLC services in the highly dense environments. For the scenarios when the number of users is large, we take the user ranking approach into consideration. To that end, designing a cell-less framework is challenging, when it is necessary to employ new scheduling techniques and schemes. However, deploying an ideal cell-less network in an Open RAN architecture which provides users with the new services is a complex and time consuming process. Therefore, we identified another challenge of designing a transition model from the legacy cellular network to the ideal cell-less one. Consequently, a cellular/cell-less coexistence period will require an Inter-Architecture Roaming and coexistence policies, which is included in the general system model.

Let us consider a set of RUs $\mathcal{M} = \{1, \ldots, M\}$ and a set of UEs $\mathcal{K} = \{1, \ldots, K\}$, where

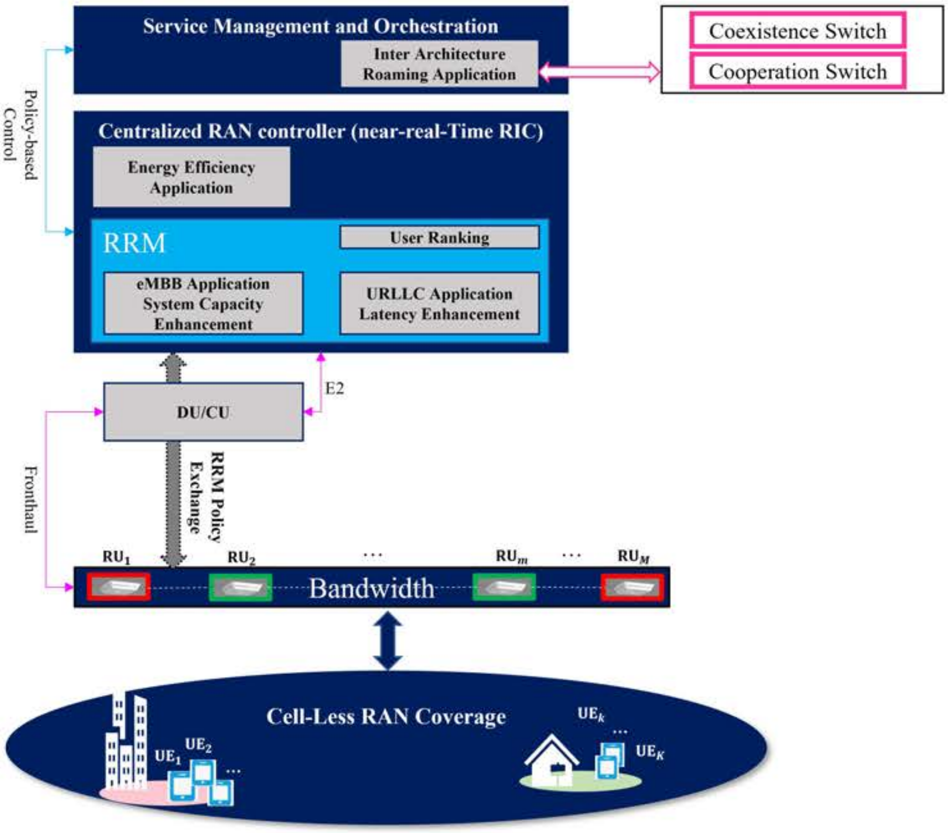


Figure 2.8: General system model of Open cell-less RAN including the focused applications.

M and K are the total number of RUs and UEs in the network accordingly. The antennas of the RUs are considered omni-directional. The set of users under a particular RU $m \in \mathcal{M}$ coverage is denoted by U_m. Let $\boldsymbol{A}$, which is a matrix of size $K \times M$, represents the status of the users' connection to RUs. If the user k is connected to RU m, we have $A(k,m) = 1$, otherwise $A(k,m) = 0$. $\mathcal{N} = \{1, \ldots, N\}$ is considered as set of RBs, where N is the total number of RBs in the network.

In the following section, we will elaborate the state-of-the-art (SOTA) for the challenges mentioned in detail.

2.6 Challenges and State-of-the-art Solutions

In this thesis, we mainly focus on enhancing the network performance in the alignment of 5G services, usually represented as a triangle (eMBB, mMTC, and URLLC). In addition, the thesis also considers the energy aspects of the future networks beyond 5G. Several challenges are required to investigate regarding these aspects. This thesis will investigate several different network challenges related to the performance improvement of the beyond 5G network. The state-of-the-art solutions of these challenges are summarized in the next subsections. Our solution will show the light of overcoming these challenges considering the current literature.

More specifically, section 2.6.1 describes the challenges and existing literature of the Cell-less architecture in the Open RAN framework. Section 2.6.2 presents the challenges and literature of the RRM for system capacity maximization in future cell-less RAN. Section 2.6.3 discusses the challenges and related SOTA for RRM in case of URLLC and eMBB coexistence in cell-less radio access networks. Section 2.6.4 highlights the energy efficiency challenges and existing works for cell-less RAN architecture. Finally, Section 2.6.5 presents the challenges and present works for the Open RAN featured MACO network scenarios and suitable switching mode mechanisms.

2.6.1 Cell-less architecture in the Open RAN framework

State-of-the-art

The dense network in terms of high number of APs, apart from the obvious advantages related to the coverage and capacity improvement, may also be limited through the inter-cell interference. Such densified networks need to manage interference in order to keep the performance gain and system satisfactory. Considering the limitation of the bandwidth as well as other resources, the interference management needs smart control over the available resources such as resource block (RB), AP and power, in terms of scheduling and resource allocation for serving the users in the network.

The CoMP techniques [31] support the cell edge users and will improve their experience at the cost of signaling overheads and synchronization problems, which is a barrier for these techniques for practical implementation. Also due to the fixed UE/AP association in the legacy cellular mobile networks, the practical feasibility is affected by the handover problems which make it not preferable for the fast-varying channel environments in dense urban networks. These environments on the contrary need optimal dynamic and adaptive association. Dual connectivity (DC) is another technique, which resolves the mobility problems by user plane and control plane disaggregation [32], but still the fixed association will cause the UE to suffer from mobility interruption. These techniques (DC, CoMP, network MIMO, etc.) do not seem practical today due to the more remaining problems according to [33]. Hence, the new design with the introduction of the hypercell concept is proposed to solve the above mentioned problems. The hypercell proposal is based on the dynamic serving set approach and introduced by UE-Cell-Centric-Like approach. The similar concept of a logical cell covering multiple APs to serve the UEs is proposed in [34].

In the hypercell definition, a logical entity's id is replaced by the traditional physical cell id (PCI) from the user perspective, which will eliminate the radio stack layer 3 (L3) mobility needs within a hypercell and is a candidate solution for the KPI improvement in the new radio (NR). There may be some APs which overlap between different hypercells in order to resolve the mobility interruption and do "make before break" for a UE moving between different hypercells. There are different designs recommended for the channel state information reference signal (CSI-RS) from the network point of view, which allow CSI-RS port sharing and flexible Tx/Rx point (TRP) to port mapping from the network perspective [34]. In addition to the cooperation in transmitting the control channels, the interference could be managed by the multi stream data transmission that has been enabled by the hypercell concept. However, the cooperation between TRPs needs UEs' antennas to support advanced receivers. Another requirement is a new design for the reference signals in order to resolve the synchronization delay's aspects. Hence, it seems to be necessary to manage the interference in a more intelligent manner than only transmitting data cooperatively from all interfered TRPs.

In [35], the resource pooling in the frameless architecture is proposed with the adaptive resource allocation. It provides the coordination of antenna elements (AEs). However, neither virtualization (which can improve the gain of the centralization RRM aspects), nor the service slicing (which can bring more gain for network performance) is taken into consideration. Therefore, the similar frameless network is proposed in [4], which is SDN-based and supports coordination in data transmission. Moreover, it is more centralized regarding the interference management. The frameless network's coordination of transmitting nodes, was supported by the virtual gateway in [35] and the CPE in [4]. The selection of the serving sets is in a dynamic manner, while the handover requirements have been eliminated.

The mobile core network can be adapted to the SDN. Consequently, OpenFlow can be supported by that. In [4], the CoMP techniques are used to coordinate between the AEs. The OpenFlow controller (OFC) supports the coordination of centralized resource allocation and the route selection with a dynamic set selection. According to [4], there was still a requirement of the additional investigation for the implementation aspects for scaling up the network with the higher order of users and their corresponding serving APs. In [3] the author has analyzed evolved C-RAN. The frameless concept, built on the works in [4], [35] was proposed with the implementation of cloud computing to support the centralized processing. Although it is taking the centralization and the virtualization advantages for the new frameless topology, there is dependency on the different entities of the virtualized network. Therefore, the software upgrade and the network scaling up are the complex aspects. The O-RAN architecture was analyzed in the initial steps in [36], by support of the virtualization in combination with SDN. It is now feasible to make RAN open and flexible for implementation thanks to the Open RAN architecture and specifications, which was also addressed in [4]. In [36], the SDN controller is connecting to the virtual BBU elements through a SDN agent in order to pass the controlling flows to the Virtual BBUs. However, it is performing within the cellular topology. The authors in [37] proposed the SDN-based handover management approach and also addressed the way for creation of virtual e-NodeB to support better performance for handover.

Beyond State-of-the-art

The cell-less architecture is an enabling technology with a complete combination of openness, virtualization, softwarization, and network cooperation. In the following section, the cell-less technology is proposed to be implemented through an Open RAN architecture, which could be supervised with the near real-time RAN intelligent controller (near-RT-RIC). In this thesis, the cooperation is addressed for intelligent and smart resource allocation for the entire RAN. Also, the handover will be completely removed as a result of the elimination of the cell boundaries.

2.6.2 Efficient Radio Resource Management for System Capacity Maximization

State-of-the-art

With an incredible surge of mobile traffic from the second generation (2G) towards 5G demands, massive requirements of capacity and stringent quality of services (QoS) are needed. These could be managed by a number of technological features e.g., wider bandwidth, new radio interfaces, antenna configuration, and different levels of network densification. The concept of cell-less refers to the network where users can dynamically communicate with one or any required number of APs if necessary. It has been proposed to overcome the major limitations of cellular networks, e.g., network convergence, load balancing, frequent handover, and interference through the horizontal convergence in celled architectures of APs [30], [38], [39]. In a conventional cellular network architecture, the RU from a specific service provider is allocating resources by assuming only the local knowledge of the radio environment and underpinning its users. The global network situation (including users connected with its neighboring RUs and the available radio resources of the RUs) is not accounted for. The internal competition for the resources (i.e., between the RUs from the same operator) causes the RUs to assign resources in a non-optimal way. This "competition" is the consequence of the cellular network architecture which needs to be shifted towards the cell-less architecture for the next generation RANs (NG-RAN) of 6G networks. The concept of "small-cells" that have been largely discussed for 4G/5G networks [40], [41] is now evolving towards networks with many small RUs. Generally, such RUs can be deployed over a variety of infrastructure (e.g., fiber, Ethernet, radio link, etc) and can bring more degrees of freedom into the cooperation between infrastructure owners and network operators. For the cellular network architecture, OFDMA-based mobile wireless networks have generally studied the user association, physical resource block allocation, power allocation, sub-carrier assignment problems either separately or jointly, to maximize the data rate, throughput, sum rate, spectral efficiency, and achievable data load of the networks [42]–[45]. These reference schemes considered resource allocation strategies for the cellular network architecture without exchanging any information amongst the users and the RUs of the networks.

However, the inter-cell interference (ICI) effect on the cellular network design can significantly degrade the capacity of the networks if the interference of the underlying RAN is not efficiently managed by the scheduler at the RUs. In the cell-less architecture, the ICI effect of the RAN can be eliminated. By managing the interference, the system capacity of the networks could be significantly improved. Several research works have already proved that the cell-less solution may improve the system capacity of the networks by simultaneously serving users by a number of RUs. The work in [46] focuses on maximizing the weighted sum rate through efficient resource allocation in multi user cell-less multiple-input multiple-output (MIMO). Recently, resource management has made a significant contribution in performance of cell-less networks. However, the deployment of any practical cell-less scheme needs to consider the finite capacity of individual RUs. On the other hand, a user-centric approach can outperform a general cell-free network where users are served by all RUs [47].

Beyond State-of-the-art

In summary, the main limitations of so-far reviewed works are as follows: most of them do not specifically address the impact of efficient resource allocation itself in the baseline cell-less network compared to the legacy cellular network. In addition, the effect of user density and environment in cell-less networks is ignored. Hence, most of them are not ensuring the applicability of the proposed schemes in different scales of network size. In this thesis we propose a cell-less networking approach along with a RRM algorithm that can significantly improve the system capacity performance over legacy schedulers. The resource allocation for an UE is performed based on the consideration of available resources from all other neighboring RUs.

2.6.3 Efficient Radio Resource Management for Latency Minimization in case of URLLC and eMBB Coexistence

State-of-the-art

Latest 5G wireless communication technology is being deployed all over the world to meet the tremendous demand from the existing diverse networks and services, mainly categorized as eMBB, mMTC, and URLLC [48], [49]. However, a vast range of unparalleled and evolving use case scenarios, business models, and vertical applications will also emerge along with the 5G network's ecosystem in the form of coexistence networks of URLLC and eMBB, such as smart meters, smart airports, smart amusement parks, industrial automation, real-time control, augmented reality (AR), virtual reality (VR), smart healthcare systems, intelligent transportation, etc. These emerging applications would cause a scarcity of radio resources due to the need to guarantee the reliability of low latency services simultaneous to the presence of eMBB traffic. In addition, the increasing number of URLLC users from emerging applications creates challenges to state of the art resource allocation.

Recently, a new RAN architecture known as cell-less (or cell-free) [30], [50] is proposed to provide high spectral efficiency, flexible and cost-efficient deployment, ensure high quality of service and benefit from low path loss propagation conditions. In the cell-less architecture, the cell boundaries are removed from the user equipment (UE) view point. In most of the recent literature illustrating the advantages of cell-less mMIMO over legacy architectures, the relevant KPIs for eMBB service type are used [51]. Furthermore, the analysis in few recent works such as [52], [53] are conducted over URLLC requirements with short packets. However, they focus on the scenarios with large number of transmitters in comparison to the number of UEs. Hence, they neglect the latency performance degradation in highly loaded scenarios where there is a large number of URLLC UEs. They mainly focus on providing a large number of transmitters to support users, which has a high practical deployment complexity.

A relevant example of a scenario with a large number of URLLC users is smart metering networks (SMN). In such types of networks, data collection from many meters or devices and data transmission over long distances need to be enabled. Low latency is a highly demanded requirement which will directly impact the efficiency of smart planning for different types of energy (e.g. gas, electricity, and water). SMN allows people to understand how they are using energy and where they might be able to economize given their usage levels [54], [55]. An efficient low latency and highly reliable data transmission will afford the near real time planning transmission regarding energy consumption and could significantly affect the cost of energy for consumers and providers. In addition to that, it will enable many opportunities for the governments in terms of managing the country's level of energy consumption. Assuming the large number of devices which need to send and receive short packets, with very low latency transmission, the number of resources will be a bottleneck causing a harmful competition. Note that the consumer could also expect to trace the consumption summary to have better experience from SMN. Therefore, a limited number of eMBB devices could be existing in the network as well.

Other representative use cases are smart airports and smart amusement parks which need a low latency smart planning for many devices carrying different services. In these use cases, delivery of such efficient planning with low latency is critical to control the human traffic, service scheduling, etc. Industrial 5G is a promise to support private networks for URLLC service delivery. Big industry players are working to deliver industrial 5G, enabling smart energy protocols and ensuring high private and global digitalization revenues [56], [57]. There have been several studies in the literature reporting resource allocation mechanisms enabling coexistence scenarios of URLLC and eMBB [58], [59]. The authors in [58] proposed a resource scheduling scheme by optimizing the bandwidth pre-allocation for eMBB services and minimizing the decoding error rate of the devices carrying URLLC services to meet the needs of the system. Mengge *et al.* proposed a two-stage resource allocation scheme for eMBB and preference-based URLLC resource preemption schemes for bandwidth-sensitive URLLC and time-sensitive URLLC respectively to improve the reliability of eMBB traffic [59]. The URLLC requirement is characterized by the 3GPP as 99.999% reliability with an end to end latency less than 1 ms [60] which is planned to be extended in the new release with additional features, e.g., anything reality, 5G NR for high frequency, etc [61]. However, these works do not consider the impact of a higher number of URLLC users for the use cases and applications. Some research efforts have been invested in the context of using the advanced allocation of frequency resources to the eMBB and URLLC services [62]–[64]. However, these works exhibit a lower use of frequency resource utilization. To alleviate this limited resource utilization, different frequency resource allocation schemes were proposed in [65]–[67]. These research schemes mostly allocate frequency resources firstly to the eMBB as per throughput demands where some resources are reallocated to URLLC if URLLC traffic comes in the meantime. However, these papers do not reasonably account for the impact of the URLLC devices on eMBB services.

Considering the resource limitations in wireless networks where URLLC and eMBB users might coexist, improving the network performance for each group in a way that does not degrade another group's criteria is an important challenge. Inter-cell interference is addressed in many works, such as [68] and [69], using power boosting coordination or sleep mode techniques supporting URLLC services. In the context of inter-cell interference and coexistence of URLLC traffic with eMBB traffic, [70] presented a joint link adaptation and scheduling policy which addressed these challenges. Many other works (e.g., [71] and [72]) proposed joint scheduling techniques for URLLC and eMBB traffic using approaches like deep supervised learning or preemption-aware subspace projection through (TD, FD) schedulers. However, these solutions do not cover scenarios with a large number of URLLC devices. This challenge would become worse for resource allocation in case of a highly loaded and massive number of URLLC users in mixed URLLC and eMBB scenarios. This situation introduces a high competition for the resource blocks which tends to increase the latency of the waiting period of the URLLC packet with the increasing number of users, thus hampering the main attributes of URLLC services. In [73], the authors proposed a novel framework, which includes a massive URLLC scheduling technique, the network assisted traffic model, and the QOS-aware congestion avoidance algorithms. The proposed scheduler consists of TD and FD resource allocation. However, the inter-cell interference management is not considered. An attractive centralized RAN (C-RAN)-based multi-cell scheduling algorithm is proposed in [74]. The TD scheduler solves the user association problem centrally, while the FD scheduler performs RB allocation for the users associated with the same cell. However, the FD scheduler does not mitigate the inter-cell interference because of its competitive algorithm for RB allocation. Therefore, throughput performance will be degraded when the number of users increases. It is obvious from the above literature that existing techniques and approaches of the radio resource allocation and management of the 5G systems will not be sufficient to satisfy these emerging and envisaged use cases in the cell-less paradigm, rather it would require to introduce new schemes of RRM.

Beyond SOTA

Clearly the impact of a high number of URLLC service requests from the envisioned use cases could impose operational challenges on network performance for the coexistence scenarios. However, the above mentioned literature does not reasonably address the challenge of applicability of such solutions in highly loaded scenarios with a massive number of devices. It is observed that in many cases the latency over large scale scenarios is still a limiting obstacle for relevant use cases. In addition to that, in such environments, even with a limited number of eMBB users being available, their experience is not satisfactory due to the received interference from new admitted users in scheduling time intervals. This interference is neither well considered nor managed in the above literature.

To the best of the authors knowledge, no literature has been found so far investigating the impact of highly loaded massive URLLC users in a mixed URLLC and eMBB traffic use cases that considers mitigating existing interference in the network. Therefore, efficient RRM is required to minimize the latency of URLLC while enhancing the throughput of eMBB for such coexistence networking scenarios. This thesis aims to contribute to fill up these research gaps.

2.6.4 Energy Efficiency Enhancement for Cell-less architecture

State-of-the-art

Escalating traffic demands for different use cases and new applications of the evolving mobile communications generation (i.e., 5G and beyond (B5G)) lead to the action requirement from the operators to expand their networks for supporting more capacity. At the same time, the increased traffic is consuming huge energy in the wireless networks, which impacts greenhouse effect significantly. Research communities from both academia and industry are now focusing on novel technologies, architecture, infrastructures, and solutions to execute the capacity expansion plan while minimizing energy consumption as possible from both access and backhaul networks [75]–[77].

Recently, the cell-less architecture (or cell-free)[1] [50] is approached to provide high spectral efficiency, flexible and cost-efficient deployment, ensure high quality of service and low path loss propagation conditions. In the cell-less architecture, the cell boundaries are removed from the UE view point. However, it is not practical to serve all UEs by the entire available transmitters due to the capacity constraint of a particular transmitter. In

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[1] "Cell-free" is the term which is often used when referring to the advances of the physical layer transmission techniques using massive MIMO. Here we use "cell-less" as a more general term pointing to a new architecture, independently of the type of transmission used.

order to have a practical and feasible architecture, new technical solutions adoptable to the architecture are needed to meet the KPIs and afford the resource consumption, including energy. At the same time, the industry players are interested in novel architectures involving green implementation and improving the network EE to reduce energy consumption. The open RAN solution has been considered as an enabler for EE in 5G Networks [78]. Therefore, it requires novel technologies being customized for an energy efficient implementation. The key contributing operators in open RAN just started to focus on energy performance parameters and solutions for candidate technologies and architectures [79]. Having the different traffic load over time based on the user condition diversity leads to huge amounts of wasted energy by keeping the APs with the same transmitting power status all the time. Considering the sleep mode technique as a recognized feature to improve EE, proper management of energy utilization in the APs will enhance the network EE. Therefore, in this thesis, we propose an energy efficient sleep mode scheme for a cell-less RAN architecture in 5G and beyond 5G networks.

Although the newly deployed small cells use a lower transmitting power, still the circuit power consumption is high. As a result, a significant enhancement in energy saving is feasible by switching off the low loaded APs. Cell zooming [80] is considered as one of the potential candidates of green communication deployment in order to optimize the transmitting power. Not only power, but management of the entire radio resources (considering RUs among these resources) is an effective aspect of green communication, which will ensure the feasibility of a new solution and its interest for the operators. As the major part of the network energy consumption occurs on the base station/AP (BS/AP) sites, the joint energy saving through small cell BS/AP sleeping and interference coordination mechanisms were addressed in [81], [82]. The authors proposed an online solution to minimize the energy consumption as a function of aggregated users' traffic with QoS boundaries for users. The two-level controllers in global and local states support the performance of the algorithm. An efficient traffic-aware user association method to switch off BSs with traffic below a predefined threshold is proposed in [83]. In this paper the traffic across the BSs is monitored continuously to detect best candidate resources to save energy. However, the effect of switching off BSs on the amount of data transmission ratio per energy unit is not considered. In [84], a grid-based traffic map BS switch off algorithm is proposed to reduce the energy consumption in dense 5G networks. There are different types of BS/AP mode selection techniques in [85], considering if they are applied in a competitive or cooperative manner. Competitive schemes would be performed at each BS/AP without considering metrics regarding others. On the other hand, cooperative schemes are applied to the network considering other BS/AP status in switching off. In [86], authors proposed a new scheme to mitigate the network interference through selecting the unnecessary femtocells to enter sleep mode and enhance network EE. This mechanism allows the UEs in any femtocell in sleep mode to reconnect to other femtocells.

In [94], the authors presented a detailed survey about energy efficient resource allocation in shared RAN. The work gave an overview with a classification of energy efficient schemes and highlighted gaps. Powering on/off RRHs according to load variation is considered among the self-optimization techniques for achieving EE. The proposal in [87] leveraged an EE sleep mode criteria in BS/AP to optimize the network energy efficiency through total power minimization using a load transfer algorithm. However, the scheme ignored the network traffic load loss caused by small cells that are unnecessarily switched off. A network throughput-based sleep mode scheme is proposed to enhance the total EE and reduce power in [88]. In [89], a power minimization technique for cell-free massive MIMO networks is proposed, which makes inefficient APs sleep during non-busy hours. Although the simulation results of this paper show that the proposed low complexity algorithm reaches near optimal performance regarding power consumption, while satisfying the minimum spectral efficiency requirements of all users, it is not addressing the transmission rate per energy unit as the parameter to be optimized, not yielding a solution of the problem being targeted here. EE optimization problems are managed through throughput optimization and energy saving models. However, energy saving will cause throughput degradation, since both parameters are highly correlated. Therefore, it is needed to focus on a joint optimization to obtain an optimum EE [90], [95]. Minimum individual EE is ignored in the so-far reviewed joint optimization literature. In [96], the authors proposed cell-level EE enhancement, instead of network-level, through adaptive BS sleep control to maximize the minimum EE of active BSs. However, the impact on network EE and traffic losses of switching BSs off is not considered. A sleep control technique is proposed in [97] to jointly improve network EE and throughput. The proposed technique maintains the network throughput in 99% of the cases when there is no implemented sleep mode

Table 2.2: Energy Efficient AP ON-OFF Switching Approaches in Literature

Reference	**Objective**	**Contribution**	**Limitation**	**UA**	**LD**	**IM**	**TREU Max.**	**EEE Stability**	**EE Max.**
[80]	PC Min.	Centralized and distributed cell zooming AP on/off switching according to traffic load and spectral efficiency	A, B, C, D	Yes	Yes	No	No	No	No
[81]	EE Max.	Interference-based AP on/off switching to enhance capacity (and EE) in HetNets	C, D	Yes	No	Yes	No	No	Yes
[82]	PC Min.	(a) Online learning approach using AP on/off switching (b) Propose user association, power control, and interference management accordingly	A, D	Yes	Yes	Yes	No	No	No
[83], [84]	PC Min.	Traffic load-based AP on/off switching to minimize power consumption	A, C, D	Yes	Yes	No	No	No	No
[85]	PC Min.	Captures spatio-temporal fluctuation of traffic demand to jointly optimize clustering for cooperative transmission and AP on/off switch	A, C, D, E	Yes	Yes	No	No	No	No
[86]	EE Max.	Spectrum management to mitigate interference and enhance individual and system capacity and EE in addition to performing UE-BS association	C	Yes	Yes	Yes	Yes	No	Yes
[87]	PC Min.	Spectrum and load sharing for AP on/off switch	A, C, D, E	Yes	Yes	No	No	No	No
[88]	EE Max.	Throughput based AP on/off switching in HetNet	C, D	Yes	Yes	Yes	No	No	Yes
[89]	PC Min.	Utilizes optimized transmit powers to enable sleeping BSs and achieve EE load balancing in cell-free networks	A, C, F	Yes	Yes	Yes	No	No	No
[90]	PC Min. EE Max.	(a) Cooperative sleep mode for group-based sub-frame configuration per BS (b) Focused on energy saving and EE optimization simultaneously via fairness-based sub-channel allocation and power allocation	C	Yes	Yes	Yes	Yes	No	Yes
[91], [92]	EE Max.	Interference contribution rate-based AP on/off switching considering the serving signal strength measurements of UEs and load of BS	D, G	No	Yes	Yes	No	No	Yes
[93]	EE Max.	Propose goodness of-fit (GoF) AP on/off switching based on non-uniform spatial traffic density to adapt to both the number and the statistical distribution of UEs in the cell-less network	C, D, E	Yes	Yes	No	No	No	Yes
[30]	PC Min.	A sleep mode scheme is proposed in several states including transferring, ready, listening, and sleeping to decrease energy consumption in cell-less networks	A, C, D	Yes	Yes	Yes	No	No	No
Proposed ($3 \times E$) Scheme	EE Max.	(a) Interference contribution rate-based AP on/off switching according to the serving signal strength measurements of UEs and load of APs in cell-less RAN networks. (b) Through 2 steps scheme to maximize network EE and control traffic loss, EE enhancement performance is kept stable in higher user density	H	Yes	Yes	Yes	Yes	Yes	Yes

A = Not focused on EE maximization; B = Inconsistency between cells may cause uncovered area using cell zooming;
C = Stability of EE performance enhancement is not considered at higher user density;
D = Not focused on increasing the amount of transmitted data per energy unit;
E = No interference management; F = More focused in non-busy hours;
G = Stability of power saving is not considered at higher user density; H = Not considering minimum power consumption as targeting EE maximization.
UA = User Association; LD = Load Management; IM = Interference Management; TREU = Transmission Rate per Energy Unit;
EEE = Energy Efficiency Enhancement; PC = Power Consumption; EE = Energy Efficiency.

technique. However, it is not providing a stable performance against traffic fluctuations when the number of UEs is increased. This is because of not handling the interference within a dynamic load of the network. The proposed on/off switching algorithms in [91], [92] improve the network EE and the total data rate, while controlling traffic losses considering the interference between BSs. However, it is required to consider the number of transmitted bits per energy unit to ensure that the EE optimization is achieved in the network irrespective of the user density. Hence, we should maximize the network EE through an efficient scheme applicable to the networks with any user density. Then, individual EE degradation because of co-channel interference increment by increasing the density of users is avoided. Otherwise, the network would not be energy efficient in highly loaded scenarios.

Moving toward 5G and beyond network enablers, considering the novel cell-free architecture, the authors of [98] proposed a power consumption model to have an improved EE by the analytical determination of pilot reuse factor, BS/AP density and number of antennas per AP for the cell-free massive MIMO network, which would improve the EE. The performance was reflecting a certain optimal point for the number of users, antennas and BS/AP density. Beyond that certain point, the EE per area would be decreased due to interference increment. In [99], the authors proposed a power allocation scheme for the cell-free massive MIMO network and by combining with the BS/AP selection algorithm in order to control the power consumption of the backhaul links, the EE of the network was improved while addressing the fact that for a particular user, only a small number of antennas are actively serving it. In [93], the authors proposed a dynamic energy-efficient sleep mode selection for the cell-less millimeter wave massive MIMO network that is adaptive to the number and statistical distribution of the UEs in the network. Traffic load management within BS/AP sleep mode selection techniques are also proposed in cell-less networks [30]. The SDN-based network architecture [75], thanks to a centralized controller support for RAN, is a strong enabler to make the cell-less implementation practical. Table 2.2 shows a comparison and key differentiators of existing energy efficient sleep-mode techniques in the literature.

Beyond State-of-the-art

In the existing proposed solutions, the energy efficiency performance has yet been an important topic for novel architectures such as cell-less, among the enabling technologies of 5G and beyond networks. The target of this work is to design a customized energy efficient technique which can bring the cell-less network implementation practical and advantageous from the energy consumption and implementation complexity point of view for the open RAN network solutions. The so far reviewed papers are not comprehensive and not fully adapted to the cell-less architecture in which there are no cell boundaries. The UE is already distinguishing the entire radio resources as a common pool where the RAN is transparent from this perspective. Moreover, the UE does not need to do handover in a cell-less architecture and thanks to this, the cooperative association scheme could be implemented without extra signaling due to handover procedures but with higher energy efficiency performance through applying our proposed sleep mode selection scheme customized for a cell-less design. This scheme would consider the fact that the UE needs to be able to be served by any particular radio resources within the time intervals in an energy efficient continuously running converged network. To the best of the authors' knowledge, no literature has been found investigating network EE optimization, through increasing transmission rate per energy unit, that assures the stability of the performance enhancement irrespective of the demand and density of users. With focus on these research gaps, aiming to optimize the total network EE and the minimum EE of the active RUs in addition to managing their interference contribution, an energy efficient scheme is proposed. We have considered an efficient customization through a two-step sleep mode technique, in a way that EE performance enhancement against user density fluctuation in the network will be managed. Our scheme will enhance network EE significantly and outperforms the previous works. Hence, the main advantage of our proposed ($3 \times E$) scheme is the fact that it is optimizing the minimum EE of active RUs and network EE within different user densities thanks to our applied strategy for selecting sufficient RU candidates to save energy and enhance data transmissions per energy unit. The scheme could save energy not only in the non-busy-hours, but also enhance energy efficiency in busy-hours. This contrasts with the reviewed literature, which did not maintain efficient power saving when the load increases because of the user density increment. Although it is needed to re-associate a higher number of users from highly loaded sleeping RUs in our scheme compared to the referenced techniques, the proposed criteria will manage and avoid high traffic loss and performance degradation instead. In addition to this, handover procedures are removed as a benefit of using the cell-less architecture.

2.6.5 Multi-architecture coexistence network (MACO)

State-of-the-art

In recent times, the vast amount of mobile data traffic generated from wireless devices and Internet of Things (IoT) was planned to be managed by the new wireless standard, i.e., 5G which is being rolled out across the globe with high network densification [100], [101]. Densification of networks in the 5G communication leads to some performance limiting factors and drawbacks such as interference, convergence, frequent handover, and load balancing [30], [102]. To overcome this interference which causes performance degradation, there are different methods such as multi antenna transmission technology [103], [104], massive MIMO [105], [106] and coordinated multi point (CoMP) techniques. The interference management techniques are complicated due to backhaul requirements for channel state information (CSI) exchange [107]. Also, there are different types of CSI which are important in terms of supporting types of CoMP and in some researches are not selected as the practical one. Author [108], [109] mentioned about the CSI feedback that is supported by LTE release 11 and used in CoMP. For the techniques such as network MIMO and CoMP, there are practical issues and may not allow to achieve the system gain up to the level of theoretically proven gain in ultra-dense networks [110]. Therefore, in such a dense network, assuring stability of the system performance and further improving it, could be solved by dividing the network into smaller regions to increase its management robustness. The proper interference management topologies enabled by cloud RAN (C-RAN) [111] dynamically divide UEs into clusters. In C-RAN architecture using CoMP technique the signals through RRHs are passed to the central BBU pool [112], [113]. In this regard, as a 5G enabler, partitioning the network and using small cells is considered as another solution [114]. The small cell concept opens the doors of advantages such as higher capacity and the possibility of using these benefits in an indoor scenario as well as outdoor. The virtual small cells are enabled by virtualization of the network functions and PHY/MAC splitting on RRHs. In some scenarios where one small cell cannot meet power requirements of the users, clustering is required [115]. In [116], the authors focused on small cell clustering. Grouping a set of APs is a solution which manages the interference in terms of proper scheduling and transmission techniques through a group of cooperating small cells.

Beyond State-of-the-art

Besides, the cell-less approach appears as one of the solutions to overcome the existing discrepancies of legacy cellular networks (e.g., frequent handovers, inter-cell interference, and extra load of information exchanging between the cells). The cell-less RAN architecture needs to use the RRHs in a pool by considering them as resources in order to remove the cell boundaries. To allow matching the most relevant resources to different users in an efficient and dynamic manner and to address interference handling, a different scheduling algorithm is required. Therefore, the competitive scheduler in the existing cellular architecture (e.g., Round Robin (RR), and Max-SINR) needs to be exchanged with the cooperative scheduler in the cell-less architecture which is also considered in this research.

The above mentioned research indicates the useful techniques to improve the 5G system performance. Deployment of the proposed solutions enabling the novel RAN architectures in a cell-less oriented manner with a network wide integration is a time consuming and complicated procedure. However, it needs to start being integrated with the available infrastructure of the telecommunication industry. Hence, the feasibility of roll out should be taken into consideration, which means the combination of existing and the new architecture should be enabled. The combined network could be lasting till the entire network be migrated to the ideal architecture in the future. For this regard, the proposed architectures should have the option to coexist and be able for interconnections with the other architectures in an open ecosystem. Considering switching techniques and a cooperative approach for the novel proposals will open the doors and facilitate maximum utilization of the existing network frame as well as minimizing the roll out procedures and cost-efficient viewpoint. To the best of authors' knowledge, no research investigates the efficient scheduling mechanisms for the multi-architecture coexistence network scenarios with the impact of using massive numbers of users to improve system performance.

Our proposed approach sheds light on using coordinated approaches in the Open RAN featured multi-architecture coexistence (MACO) networks. This novel network design is focused in this research opening the ecosystem evolution which was not considered in available systems.

2.7 Research Questions

This thesis targets the enhancement of the cell-less radio access network architecture for the future generation wireless network in several aspects such as architecture integration with Open RAN framework, efficient RRM schemes for capacity maximization and latency minimization, energy efficiency, and multi-architecture coexistence scenarios. Several research challenges are addressed in these aspects. To this end, this thesis focuses on the following research questions:

- How can a cell-less networking be integrated in the Open RAN framework to avail more networking benefits? In this thesis, a cell-less networking approach is proposed for the integration of Open RAN framework to facilitate more networking benefits.
- How to design an efficient RRM for cell-less architecture to enhance the system capacity? In this thesis, an efficient RRM scheme is proposed to increase the system capacity.
- How to develop an Enhanced RRM scheme for cell-less architecture to minimize latency in the URLLC and eMBB coexistence network scenarios? In this thesis, an efficient RRM scheme is proposed to solve these challenges. In this aspect, two schedulers are proposed to minimize the latency for different network sizes.
- How to improve energy efficiency for the cell-less RAN architecture? This thesis proposes an energy efficient enhancement scheme to assure a stable performance enhancement and maintain an efficient power saving in peak-traffic hours.
- How can we design a multi-architecture coexistence network scenario, i.e., cell-less and cellular? In this thesis, a multi-architecture coexistence network scenario is proposed to enable inter-connection of different architectures through coexistence

and cooperation logical switches in order to enable smooth deployment of a cell-less architecture within the legacy network.

2.8 Concluding Remarks

This chapter has provided an outline of the relevant research undertaken to promote the novel cell-less RAN architecture in the Open RAN alignment for the next generation wireless communication networks. In this context, this chapter has presented an overview of the beyond 5G networks, radio access networks and evolution of RAN, RRM and energy efficiency. Several challenges related to these attributes have been mentioned. At the end, this chapter identified several gaps in the literature and mentioned research questions for this thesis. Chapter 3 will present the cell-less RAN architecture in the Open RAN framework.

Chapter 3

Cell-less architecture in the Open RAN framework

Cell-Less concept enables the network resource unification, allows connectivity continuation, promotes the entire available resources being opened with an efficient network performance and supports the Open RAN architecture by making an open connection for the entire available RAN entities from any vendor. As stated in Chapter 2, the concept of cell-less architecture in the Open RAN framework is presented in this chapter which includes the architecture, cell-less topology compatibility with the Open RAN strategy, cell-less establishment schemes, and signalling flow diagram. This research is part of the work in the granted patent [7].

The rest of the chapter is organized as: Section 3.1 shows the architecture description; Section 3.1.1 discusses the cell-less topology compatibility with the Open RAN strategy and Section 3.1.2 studies the cell-less establishment scheme with signalling flow; finally, Section 3.2 draws the concluding remarks for this chapter.

3.1 Architecture Description

The new network architecture, named cell-less, is expected to provide the higher performance gain for the network. It is considered as a solution aiming to create a wider amount of resources for the user by eliminating the cell-boundaries, as well as solving the limiting problems such as frequent handover, mobility management, and network scalability. However, the new topology for cell-less architecture is required to make the deployment practically feasible and cost-efficient.

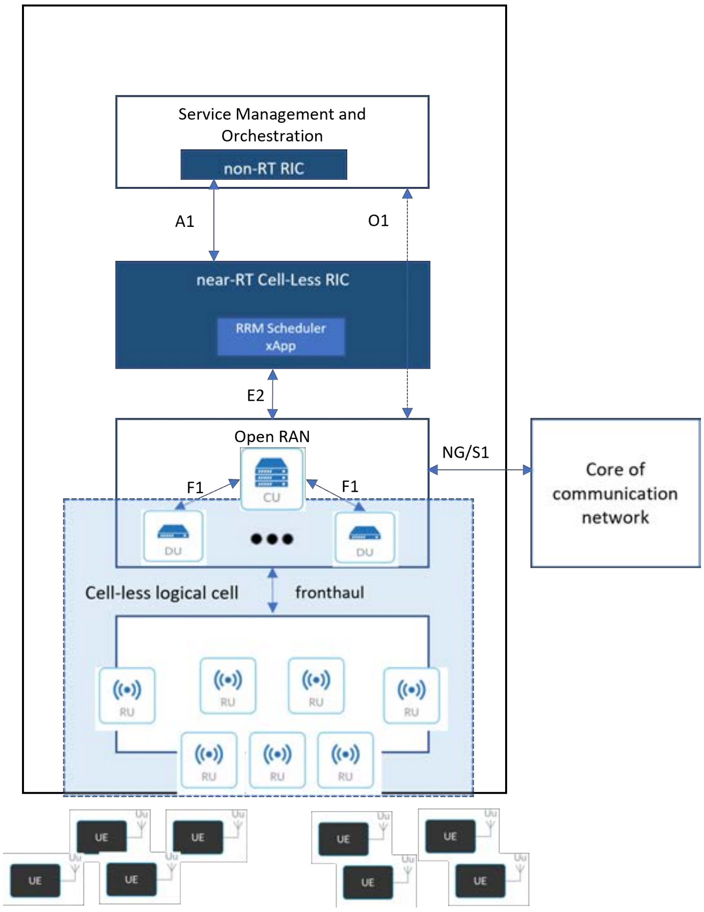

Figure 3.1: Cell-Less topology compatibility with O-RAN architecture.

In this section, we propose the solution to provide RAN coordination by pushing an intelligent coordination through the virtualized and open network's elements. Using Open RAN infrastructure can open the possibility of connecting multi-vendors' DU-CU and the legacy LTE and 5G components through the open interfaces. Thanks to this, Open RAN enables the vertical convergence for the cell-less within the heterogeneous network. The proposed network is based on the disaggregated RAN, which provides deployment flexibility and adaptability to the Open RAN architecture. The RAN needs to be supervised by the near-RT-RIC or any other controller to make coordination between the necessary serving points. There can be a scheduler agent per DU as a terminal to pass the scheduling policies to the RUs, those that are deployed within the coverage of the common scheduler. However, each DU is either supporting multiple RUs or mapping to only one RU.

The common scheduler is responsible for the entire RAN and the scheduling policies are pushed through the near-RT RIC connecting to the scheduler agents at DU/CU(s). The near-RT-RIC (or other type of controller) will supervise directing the RRM schemes to the CU(s), DU(s) and RUs. The common scheduler has full information of the entire radio network for scheduling, while the agents support coordination between different RUs. Thanks to the agents at DUs, there is no requirement of coordination between the DUs. The scheduling that needs to be performed on RUs, is informed to each corresponding DU/CU agent and based on the available header identity (addressing a particular RU) for each packet, the DU is directing the received scheduling policy to RUs via the DU agent. Based on the architecture shown in Fig. 3.1, the cell-less topology is performed to make a cell-less RAN generalized for all available types of the RAN. The topology formation is discussed in the next section.

3.1.1 Cell-less Topology Formation Compatible with Open RAN Strategy

The cell-less RAN is supposed to be performed in such a way that eliminates the cell boundaries and, from the UE viewpoint, different RUs be transparent. To that end, UEs need to have such a connection with the unique and virtual cell-less network. Hence, the virtual network should contain all the physical cells, while a virtual cell-less id is needed for the networking aspects. Because the virtual cell-less network may be very large and dense with respect to the number of RUs, the UEs need to have less dependency to the virtual cell-less network. To avoid the dependency to a specific RU, UE should be able to be connected to the network all the time, which means it needs to keep its identity specified by the cell-less network, called UE-cell-less-Identity, accessing network while the serving point may be changed from any particular RU to another one. Therefore, cell-less RAN will allocate a specific identifier for each of the UEs independent from the serving RU, which will be maintained during the time that UE is associated with the virtual cell-less network.

The common scheduler is aware of the RBs' utilization of the whole cell-less network which is serving all the UEs. It is placed on top of all available RUs no matter supported by how many DUs. The reason for such architecture is the aim to schedule all the available resources without considering the coordination of the DUs. Whereas, it will extend the signaling overhead and scheduling complexity if DU is added to the scheduling dimensions. If the RUs are under different DUs, then the scheduler agent is available at each DU which supports pushing the scheduling to the belonging RUs under that corresponding DU. The cell-less RAN, performed through virtual cell-less network creation, is monitored and maintained through the near Real-Time-RIC.

3.1.2 Cell-less Establishment

To establish the cell-less RAN, the UE needs to camp on the virtual cell-less network. After the RIC distinguishes the cell-less architecture domain (which assumes the cell-less RAN topology/network is already triggered on by the operator/infrastructure supervisor) within the connected RUs to DUs and informs the scheduler as well, the signaling flow will start.

To initiate the cell-less establishment command, the RIC will send the Hello message to UPF/AMF or rather than core entity to any other application responsible for handover management. RIC updates the responsible entity for handover (attributes to reassociation in cell-less concept) to inform it about the status of the RUs' load, the load balancing rules and the priorities. The most important point is that it will push the RUs for virtual cell-less network establishment based on the available policies (such as coverage area's scope, frequency, power and other parameters) and the UE QOS available at non-Real-Time-RIC.

The signaling flow is shown in Fig. 3.2. Then, the RAN will broadcast the virtual cell-less ID to the corresponding RUs. The target RUs will store the cell-less identity and broadcast the synchronization signals to the UEs. The UEs will use it to be associated not with a particular RAN component but with the virtual cell-less network including all the available cells. The UEs will use corresponding cell-less ID to perform the random-access channel and they will be assigned with a specific and consistent UE-Cell-Less identity. The UE identity will be maintained independent of the serving point (contrary to the PCI number), and will be used to send the measurements and the requirements to all RUs within the cell-less network. The RUs will pass it to the corresponding DU/CU and the admission control will be completed and the cell-less network establishment complete

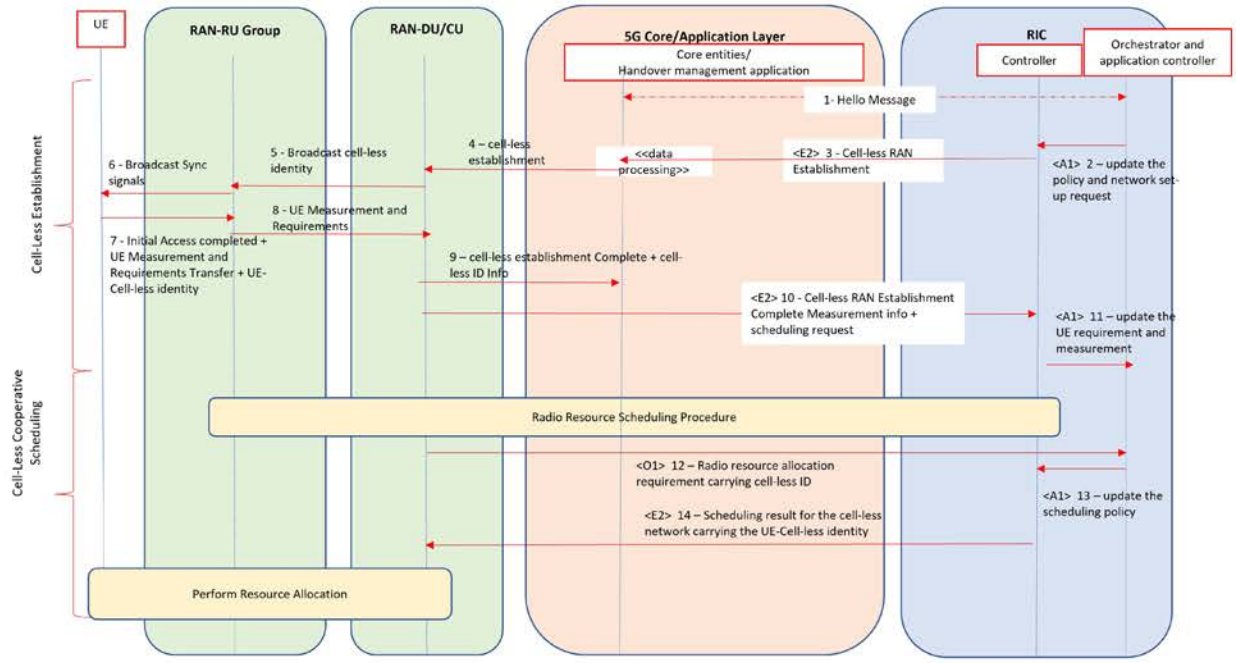

Figure 3.2: Cell-Less establishment signalling flow under O-RAN architecture.

message will be transferred to the core/open-core using the cell-less network identity. The cell-less RAN establishment is completed in this step and the updated status will be sent to the RIC carrying the measurement reports and scheduling request. The UE measurements and requirements will be sent to non-Real-Time-RIC in order to update the scheduling policy via feedback to near-Real-Time-RIC. The RIC will supervise the cooperative cell-less scheduling process with an efficient resource allocation. To this end, it will use the radio conditions and the measurement information received from the UEs for the virtually defined cell-less network instead of competitive scheduling. By having user plane data at RAN, the resource scheduling requirement command carrying the cell-less id of the network will be sent to the non-RT-RIC. The scheduling policy will be updated at the near-RT-RIC. The xApp responsible for coordinating and optimizing the resource allocation in the near-RT-RIC will send the cooperative resource allocation result to the O-RAN component and the cell-less scheduling will be performed throughout.

Having the UE-Cell-less identity for the UEs will support the frequent handover problem of legacy scheduling schemes by avoiding users from performing handover's signaling within the cell-less network. In addition, it will provide a wide pool of resources for the UEs to be scheduled cooperatively. Thanks to the Open RAN architecture, the network is flexible in coordinating all the actively-contributing (interfering) APs to cooperate in scheduling, supervised through RICs.

3.2 Concluding Remarks

The virtualization, centralization and cooperative communication which enables the cell-less RAN can further benefit from O-RAN based unifying architecture for 3GPP mobile networks to achieve the maximum achievable network compatibility. It means Open RAN and cell-less RAN are complementary approaches for each other. In this chapter, the novel architecture promoted as “smart open network” was described through the combinations of these two architectures. The requirements of the cell-less establishment were introduced and a general corresponding signaling flow was proposed. The combination of cell-less and Open RAN within the proposed principles is the start of many open optimization services. This is thanks to the RIC and the xAPPs as the RAN support functions, which is the glue of the maximum user experience satisfaction. Therefore, establishing the RAN in a cell-less manner will not only open the network vertically and horizontally, but also open the way toward efficient optimization functionalities. The cell-less RAN enabling principle is the basic requirement that is proposed here in a novel way of combination by the Open RAN architecture to switch on these advantages. Next chapter will investigate the efficient RRM scheme for system capacity maximization in the cell-less RAN.

Chapter 4

Efficient Radio Resource Management for System Capacity Maximization

Existing mobile communication systems are unable to support ultra high system capacity and high reliability for the edge users of future 6G systems, which are envisioned to guarantee the desired quality of experience. As discussed in Chapter 2, RRM has made a significant contribution in improving the performance of cell-less networks. However, the deployment of any practical cell-less scheme needs to consider the finite capacity of individual RUs. Most of them do not specifically address the impact of efficient resource allocation itself in the baseline cell-less network compared to the legacy cellular network. This chapter proposes a cell-less networking approach with an efficient radio resource optimization mechanism via a modified Genetic algorithm based solution to enhance system capacity in the cell-less architecture for future wireless communication networks. This research [8] is submitted to IEEE Networking Letters and now in the under-review stage.

The rest of the chapter is organized as: Section 4.1 states the high level architectural view of the system model; Section 4.2 presents the problem of this chapter and the proposed RRM scheme with cell-less RAN; Section 4.3 details the simulation results and performance analysis; finally, Section 4.4 draws concluding remarks from the works presented in this chapter.

4.1 System Model

The cell-less network including the RRM application is considered as it is shown in the high level architectural view of a system model in Fig. 4.1. We assume an orthogonal frequency division multiple access (OFDMA) based cell-less networking approach where all the RUs will utilize the full amount of resources, i.e., the bandwidth available for the network. The assigned RB n to k-th UE is denoted by indicator $b_{k,n}$ and will be equal to $b_{k,n} = 1$ if being allocated, otherwise $b_{k,n} = 0$. $\boldsymbol{X_b}$ includes binary indicators of any $b_{k,n}$, for $\forall k \in \mathcal{K}$, $\forall n \in \mathcal{N}$. In the considered cell-less network model, each RB is 180 KHz wide in frequency and one time slot long for 0.5 millisecond (msec). Moreover, each time slot will be carrying 7 OFDM symbols and at the frequency domain it will utilize 12 sub-carriers with 15 KHz subcarrier spacing.

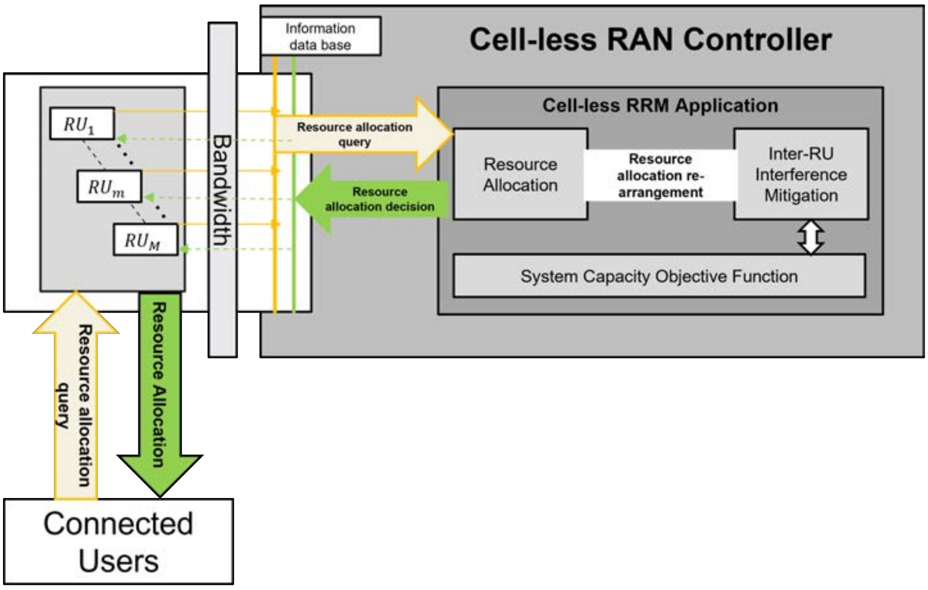

Figure 4.1: System model for the efficient cell-less RRM application.

The resources are allocated in a cell-less way which will be further explained in the next section. Let us assume $\gamma^D_{m,k,n}$ is the signal-to-interference-plus-noise ratio (SINR) of user k associated to RU m on RB n, which is defined as

$$\gamma^D_{m,k,n} = \frac{y_{k,m} P^m_n \left|h_{m,k,n}\right|^2}{\sum_{j\neq m, j\in\mathcal{M}} P^j_n \left|h_{j,k,n}\right|^2 + \sigma^2} \tag{4.1}$$

where $y_{k,m} = 1$ indicates user k associated with RU m, otherwise $y_{k,m} = 0$. $\boldsymbol{X_y}$ includes binary indicators of any $y_{k,m}$, for $\forall k \in \mathcal{K}$, $\forall m \in \mathcal{M}$. $h_{m,k,n}$ is the channel gain from RU m

to user k on RB n including the path loss and shadowing effects, P_n^m is the transmission power of RU m on RB n, and σ^2 is the additive white Gaussian noise power at each receiver.

4.2 Problem Formulation and Proposed RRM Scheme within Cell-less RAN

4.2.1 Problem Formulation

The cell-less-enabled RAN controller operates the RRM application to manage and enhance RAN performance. The proposed cell-less networking approach would dynamically adapt to the network condition by targeting the system capacity optimization as an objective function. The achievable throughput obtained through Shannon formula [2] for a particular RU m in downlink transmission for user k over RB n is

$$R_{m,k,n}^{D} = \log_2\left(1 + \frac{y_{k,m} P_n^m \left|h_{m,k,n}\right|^2}{\sum_{j \neq m, j \in \mathcal{M}} P_n^j \left|h_{j,k,n}\right|^2 + \sigma^2}\right). \tag{4.2}$$

The system capacity can be calculated as the aggregation of all active RUs throughput. Then we propose the following as

Optimization problem:

$$\arg\max_{X_b, X_y} \left(\sum_{m \in \mathcal{M}} \sum_{k \in \mathcal{K}} \sum_{n \in \mathcal{N}} b_{k,n} R_{m,k,n}^{D}\right) \tag{4.3}$$

Subject to:

$$\mathbf{C1}: y_{k,m} \in \{0,1\}, \quad \forall k \in \mathcal{K},\ m \in \mathcal{M} \tag{4.4}$$

$$\mathbf{C2}: R_{m,k}^{D} \geq R_{m,k}^{D,\min}, \quad \forall k \in \mathcal{K},\ m \in \mathcal{M}. \tag{4.5}$$

The constraint C1 in (4) indicates that user k will associate with a particular RU m and constraint C2 in (5) is guaranteeing minimum rate requirements of the users.

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[2] Any other mapping between SINR and throughput can be used as well. We take this for simplicity.

We consider the system capacity optimization problem as shown in eq. (4.3) within the proposed cell-less architecture. To improve the overall system capacity performance, we need to manage and reuse the entire network resources while satisfying the minimum QoS of the users. Therefore, the proposed cell-less RRM application will be avoiding the user service dropping along with enhancing the system level KPI. The proposed cell-less approach of networking has an opportunity to access the entire available resources by users. Moreover, the cell-less RRM application mitigates the available interference to maximize the system capacity of the networks.

4.2.2 Proposed RRM Scheme within Cell-less RAN

In this chapter, a network-wide view point of optimizing the system capacity is realized and we consider the inter RUs interference due to reuse of the resources within different RUs in the proposed design. Therefore, we divide the solutions for the inter RU interference management into two categories. In the first category, the solution is transmission cooperation by the interfering RUs while considering joint transmission as used for cell-free massive MIMO networks in [5] to maximize per user spectral efficiency. In the second category, the solution instead mainly focuses on managing the resources efficiently. As it is presented in Fig. 4.1, the system capacity improvement application would behave based on the resource allocation opportunities.

In the proposed scheme, the connected users will periodically send their channel information feedback. The corresponding RUs that receive the feedback from the users would send a query to the cell-less RAN controller carrying the available information of the channel condition, e.g., the reference signal received power (RSRP) of the serving users. Considering the channel conditions of the underlying RAN along with the inter RU interference, i.e., the co-channel interference (CCI), the cell-less RRM application will target the system capacity KPI. To enhance the system capacity, the cell-less RRM application would rearrange the resource allocation through mitigating the CCI.

The genetic algorithm (GA) is a technique that can obtain near-optimal solutions in a relatively low computation complexity, while it does not require the optimization problem to be convex [35]. Hence, we consider the modified genetic algorithm (MGA) to solve the optimization problem in (4.3). In the MGA, the optimization problem will be used as

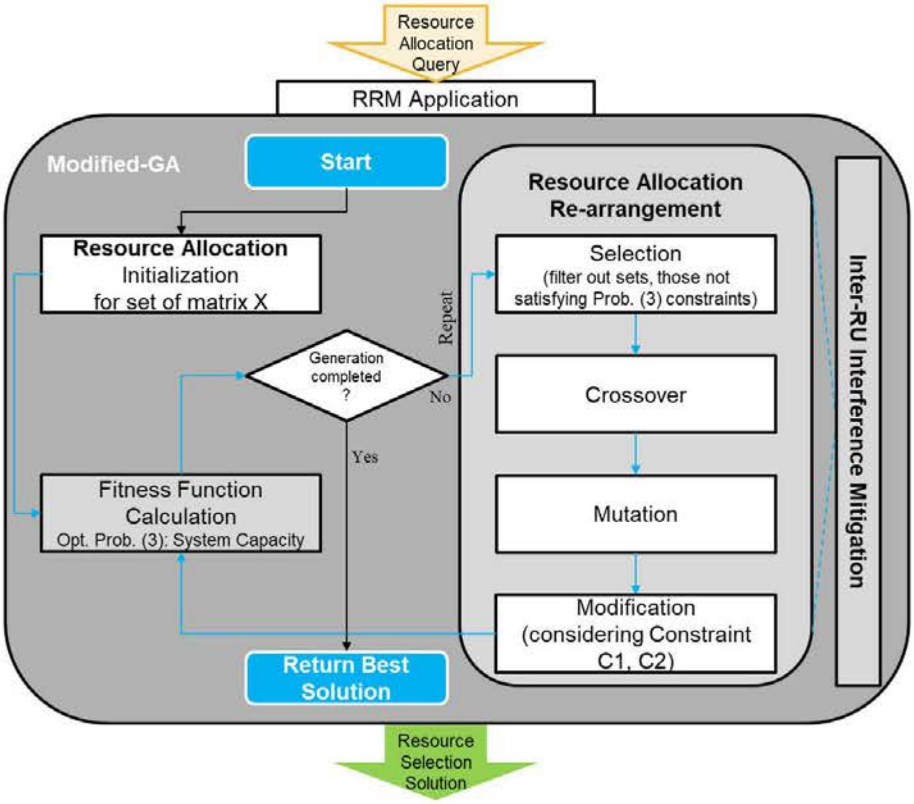


Figure 4.2: Flowchart of the modified genetic algorithm (MGA) for the cell-less RRM application.

the fitness function to evaluate the solution of allocated resources. Therefore, the Matrix X of the proposed MGA can be defined as

$$\boldsymbol{X} = \left\{ \boldsymbol{X_y} \quad , \quad \boldsymbol{X_b} \right\}, \tag{4.6}$$

where $\boldsymbol{X_y}$ and $\boldsymbol{X_b}$ are as follows

$$\boldsymbol{X_y} = \left\{ \boldsymbol{y}_{K,1} \quad \boldsymbol{y}_{K,2} \quad \dots \quad \boldsymbol{y}_{K,M} \right\}, \tag{4.7}$$

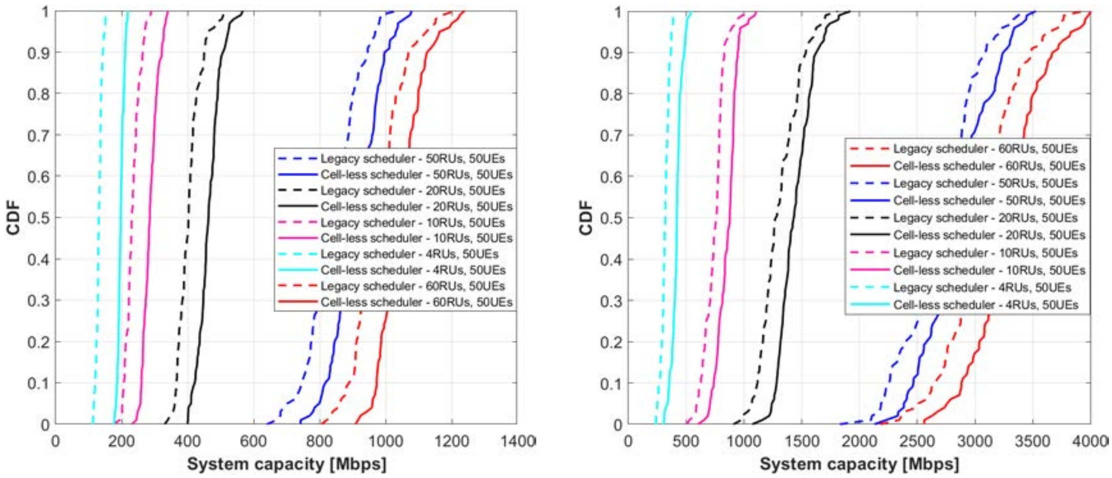
$$\boldsymbol{X_b} = \left\{ \boldsymbol{b}_{K,1} \quad \boldsymbol{b}_{K,2} \quad \dots \quad \boldsymbol{b}_{K,N} \right\}. \tag{4.8}$$

A particular matrix X represents a solution for the cell-less RRM application, where a larger corresponding fitness function reflects a better solution. A set of solutions will be initialized through the UE-RU association based on the strongest links (with the maximum RSRP) and Round Robin process for UE-RB allocation. Depending on their fitness functions, some of the solutions will be going through a four-step MGA process (i.e, selection, crossover, mutation and modification) to create a next evolved generation of solutions [9]. The generations will be evolved through re-arrangement of allocated resources (represented by $b_{k,n}$ and $y_{k,m}$ indicators) to reach the optimized solution for matrix X. The example flowchart of the implemented MGA is presented in Fig. 4.2. Through the interference awareness of the entire cell-less network, the resource allocation would be dynamically rearranged. This allocation process would improve the system capacity and evolve the entire network allocation efficiency, with a full central information awareness rather than facing performance degradation due to allocation competition. The entire competition between users on the allocated bandwidth would be taken as an opportunity by the proposed cell-less RRM application to optimize the system capacity. The more competition, the more space for efficient resource allocation, and so the more gain for system capacity. In the next section the performance analysis of our proposed cell-less architecture is described with simulation results.

4.3 Performance Evaluation and Result Analysis

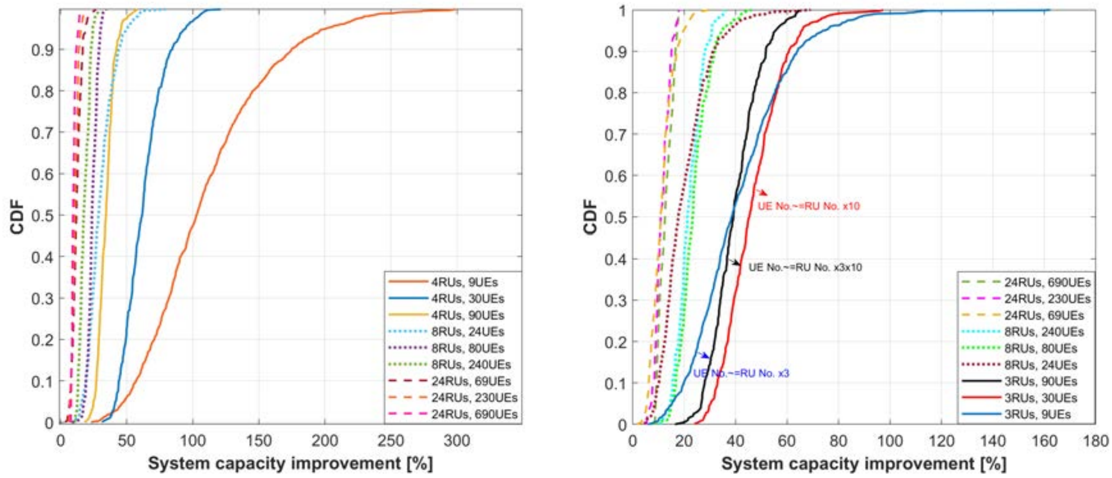
Without loss of generality, in our illustrative example, different scales of the network setups are deployed in dense urban Micro and indoor environments. The dense urban Micro environment is with a hexagonal topology with 200 m inter-RU distance, 33 dBm maximum transmit power and 15 m height for each RU. The indoor environment is with a rectangular topology with 20 m inter-RU distance, with 24 dBm maximum transmit power and 3 m height for each RU. Moreover, different numbers of RUs are configured in simulations. A 20 MHz channel bandwidth including 100 RBs is considered. The rest of the parameters which are used in this work are configured aligned with ITU-R recommendation [117], [118].

In order to analyze the network performance for different user densities, we consider different number of user configurations, guaranteeing 1 Mbps for each user as the minimum required throughput. The system capacity performance is analyzed by Monte Carlo simulations which are illustrated in Fig. 4.3a, and Fig. 4.3b, respectively. The results indicate that the cell-less networking approach with our proposed RRM algorithm shows higher system capacity performance over legacy cellular networks for different network setups in several simulated environments from [117], [118]. This is because during the resource allocation phase, the proposed approach considers the status of all available re-



(a) Indoor environment (b) Outdoor environment

Figure 4.3: CDF of system capacity comparison of the proposed cell-less RAN design over legacy cellular RAN.



(a) Indoor environment (b) Outdoor environment

Figure 4.4: CDF of system capacity improvement.

sources of the underlying RAN. In contrast, the legacy cellular RAN allocates resources competitively in a Round Robin manner (in line with the random RB mutation in MGA) from the RUs providing the highest RSRP. Due to such competitive allocation the users are receiving more interference from the neighboring cell and experience a degraded performance.

The cumulative distribution function (CDF) of the system capacity improvement due to the proposed cell-less RAN design over legacy cellular RAN for indoor and outdoor environments is illustrated in Fig. 4.4a and Fig. 4.4b. It can be observed through simulations that scaling the number of RUs is impacting the performance of the network because of the users competing in terms of accessing the resources from the RUs.

4.3.1 Performance Behaviour Insight

Based on RB level analysis, which is the reflection of channel fading conditions, and RU level analysis, which conveys the level of competition for users, we could analyze the cell-less network performance gain behavior as follows.

RU level performance analysis: The notable fact is that all the users are competing to access the resources providing good channel conditions. The more competition for resources with higher gain will create the more space to allocate resources efficiently in order to achieve more network throughput. Therefore, in general, the more RUs will cause increased resource reuse possibility. However, this would cause inter RUs user competition to happen in less share of the entire RUs. Thus, a lower capacity gain could be obtained as the result of efficient resource allocation.

RB level performance analysis: In order to analyze the RB (channel fading) level, we will categorize the RU level in two categories. The scales with low number of RUs will provide higher resource reusing efficiency per RU. The more time-frequency varying channel (i.e., outdoor environment) will eliminate the need of competition on high gain resources. Therefore, significantly it will avoid the gain of efficient resource allocation from taking competition as an opportunity. While in the setups with higher number of RUs, as the resource reusing efficiency per RU is already low, so there will be no much difference between the frequency selective fading channels (coherence bandwidth of the channel is smaller than the bandwidth of the signal) and flat fading channels (coherence bandwidth of the channel is larger than the bandwidth of the signal).

UE level performance analysis: At the end, moving toward the user level performance comparison, we will create two categories of channel fading in RB level. In the flat fading channel conditions, particularly, for the indoor environments with less time-frequency varying channel, there will be more resources providing good channel conditions. In such cases, there might not be too much benefit from user competitions in resource allocations. However, the higher performance gain could be obtained through competition for accessing a major number of these resources. Consequently, more resources being allocated per user, which means the lower number of users could be associated per RU, will provide more impact of benefiting by using the efficient resource allocation. The benefit of efficient resource allocation would be in proportion to the ratio of the more number of allocated resources and as a result, the higher gain per particular user ahead of their minimum requirements. Therefore, the higher achievable capacity gain will be provided. In the case of frequency selective channels, for outdoor environments, as there are lower numbers of radio resources providing good channel conditions within the entire bandwidth, the behavior would be opposite. The more number of the users will give the more opportunity for allocation of resources providing good channel conditions. Therefore, more users could benefit from efficient resource allocation for frequency selective fading environments. As a result, the higher system capacity gain would be achieved from the cell-less network serving more number of users.

The summary of the performance behavior insight is shown in Fig. 4.5. Understanding this behavior which is proved in Fig. 4.4a and Fig. 4.4b, makes the implementation strategy for the cell-less network clear. It is observed from the outdoor environment in Fig. 4.4b that the more number of users per RU would let the system achieve higher system capacity due to the higher gain through the resource allocation algorithm at the cell-less RAN controller. As can be seen from the Fig. 4.4b, there is an optimal number of served users per RU which in our setup is around 10 times the number of RUs at around more than 80% of simulations. Therefore, increasing the ratio of number of serving users to RU more than such optimal scale will lower the per-user performance gain. It is due to the fact that each user would not have sufficient resources for effective gain from competition to improve the system capacity. In these special circumstances, we can only satisfy allocating a number of resources for minimum throughput requirements of

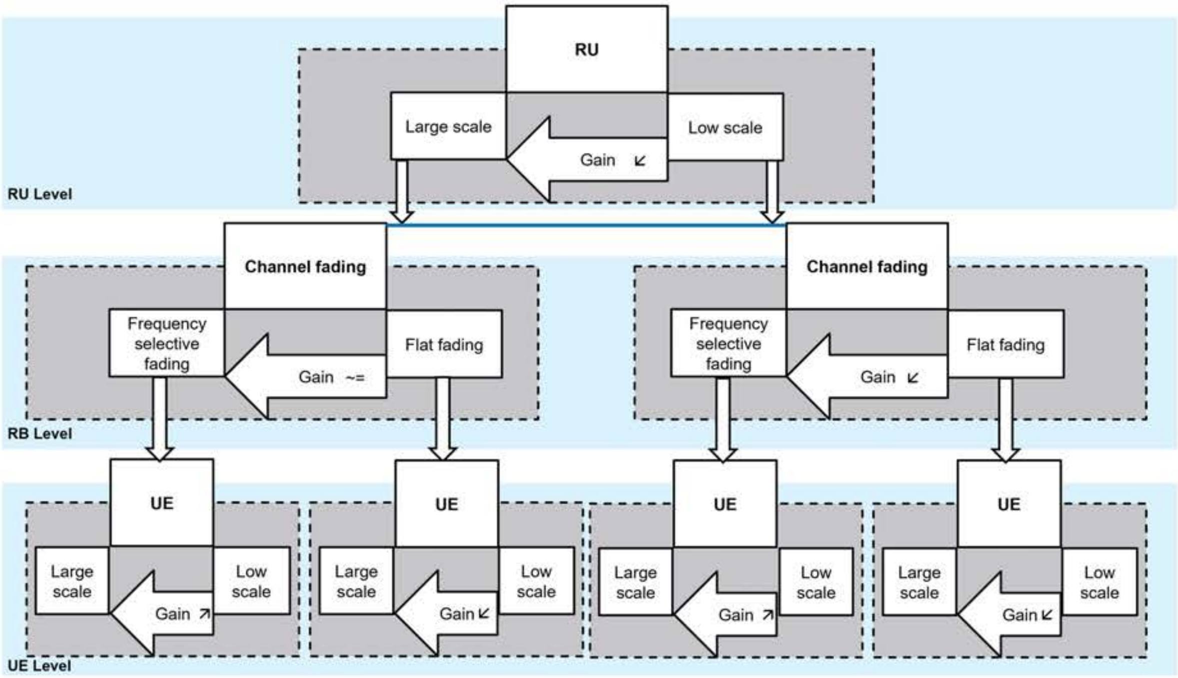


Figure 4.5: Performance behaviour insight of the proposed scheme.

the user. However, from the indoor environment simulation in Fig. 4.4a, it is observed that the lower user density setup provides more gain in system capacity considering the effect of channel fading.

4.4 Concluding Remarks

In this chapter, a cell-less networking approach was proposed for system capacity improvement of NG-RAN in future 6G networks. The potential benefits of the proposed design are highlighted which proved such benefits through several numerical simulations. The simulation results clearly indicated that significant system capacity performance improvement was achieved by shifting legacy cellular RAN design paradigm towards the proposed cell-less RAN design. In this chapter, the behavior of the proposed cell-less RAN design was investigated for one of the main KPIs, i.e., system capacity. Next chapter will explore the efficient RRM scheme, which shows latency minimization in the URLLC and eMBB coexistence network scenarios.

Chapter 5

Efficient Radio Resource Management for Latency Minimization in case of URLLC and eMBB Coexistence

Latest 5G wireless communication technology is being deployed all over the world to meet the tremendous demand from the existing diverse networks and services, mainly categorized as eMBB, mMTC, and URLLC. However, a vast range of unparalleled and evolving use case scenarios, business models, and vertical applications will also emerge along with the 5G network's ecosystem in the form of coexistence networks of URLLC and eMBB, such as smart meters, smart airports, smart amusement parks, industrial automation, real-time control, AR, VR, smart healthcare systems, intelligent transportation, etc. These emerging applications would cause a scarcity of radio resources due to the need to guarantee the reliability of low latency services simultaneous to the presence of eMBB traffic. In addition, the increasing number of URLLC users from emerging applications creates challenges to state of the art resource allocation. In this chapter, an optimization problem is formulated to minimize latency in coexistence scenarios. An efficient RRM scheme with two novel schedulers (TD and FD) is proposed for resolving this challenge. The content of the chapter is submitted as a research paper [10] to IEEE Access.

The rest of the chapter is organized as: Section 5.1 states the system model and URLLC latency components; Section 5.2 presents the proposed URLLC based RRM scheme for coexistence networks; Section 5.3 discusses the performance evaluation and result analysis; finally, Section 5.4 concludes this chapter.

5.1 System Model and URLLC Latency Components

In this chapter, we consider a downlink communication scenario with coexistence of eMBB and URLLC services. In the network, there are devices carrying URLLC services for traffic monitoring, emergency alarms, important security notices that need precision service scheduling, etc. In addition, there are eMBB devices that could fully utilize the remaining resources. There is a central controller responsible for collecting information from users and radio resources. It also takes care of synchronization of the latest resource occupation updates for further scheduling and data transmission to each URLLC and eMBB devices considering the decided RRM.

5.1.1 System Model

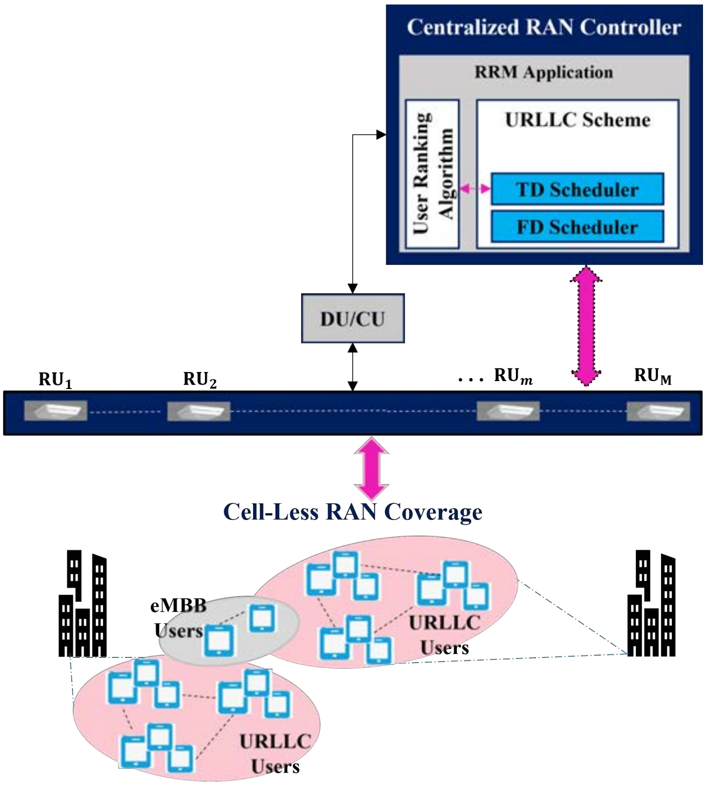


Figure 5.1: High level architectural view of a system model delivering URLLC service supporting a large number of users in addition to few eMBB users.

We assume a cell-less architecture of the RAN with an Urban Macro-URLLC environment as per ITU recommendation for URLLC scenarios [119]. In the following, let us consider a set of RUs that are distributed in the network as depicted in Fig. 5.1 and a large number of URLLC users together with some eMBB devices are randomly distributed over the entire network area. The RUs and users are each equipped with single transmit/receive antennas. The channel gain between user $k \in \mathcal{K}$ and RU m is $h_{m,k}$ including pathloss and shadowing effects. P^m is the transmission power of RU m and σ^2 is the additive white Gaussian noise power at each receiver. For each URLLC user, small payloads of B bytes arrive at the network according to the traffic model known as FTP3 in 3GPP [120], corresponding to a Poisson point process with arrival rate of λ [payload/sec]. On the other hand, full buffer traffic with infinite payload is assumed for eMBB users. To reduce the transmission time for a tight target latency requirement, a mini-slot TTI of two orthogonal frequency division multiplexing (OFDM) symbols, corresponding to 0.143 msec is considered, where users can be multiplexed on a RB resolution of 12 sub-carriers.

Each UE periodically measures the CSI for each resource element (RE) and reports a frequency-selective channel quality indicator (CQI) (it is specified in [121] for URLLC scenarios to guarantee low-probability of failure). It will allow dynamic link adaptation to select a proper modulation and coding scheme (MCS) that assures a certain block error rate (BLER) target for the physical downlink shared channel (PDSCH) transmission. The well-known outer-loop link adaptation offset is applied to improve the MCS for achieving 0.1% BLER of the first data transmission and to analyze the impact of the proposed scheme in a high load scenario. The selection of the best MCS will ensure that we satisfy the target BLER given the mutual information effective SINR mapping (MIESM) [122]. In the case of no MCS satisfying the target BLER, the packet will not be scheduled until the channel quality is improved. The users report a negative acknowledgement (NACK) for failed packets and in that case the corresponding hybrid automatic repeat request (HARQ) retransmission is scheduled by the network. The HARQ algorithm is used based on [123].

5.1.2 Latency Components

One-way URLLC latency ($\boldsymbol{L}$) contains the following components [74]

$$\boldsymbol{L} = d_{f_{a,q}} + d_{\text{tr}} + d_{\text{RUp}} + d_{\text{uep}} + d_{\text{HARQ}} \tag{5.1}$$

where $d_{f_{a,q}}$ and d_{tr} are the frame alignment and queuing delay and transmission time, respectively. Frame alignment is the random variable up to maximum one TTI, and queuing delay is the waiting time for the packet being in the RU buffer before being transmitted. It is considered that the packet is transmitted over one TTI. d_{RUp} and d_{uep} are the processing times at RU and UE, respectively. These processing times are assumed to be reduced to one TTI for each. In the case of a failure in packet transmission, the additional retransmission delay(s) is accounted for, where it is allowed up to four times retransmission. d_{HARQ} is the delay incurred by HARQ retransmissions. The minimum delay for each retransmission is equal to $d_{\text{HARQ}} = 4$ TTIs [70].

5.2 Problem Formulation and Proposed URLLC Radio Resource Management Scheme

5.2.1 Problem Formulation

In this work, we consider a network with a large number of URLLC users. Our target is to manage radio resource scheduling for URLLC users to experience their service with as small as possible communication latency subject to satisfying the proper reliability. In addition, the proposed scheme is applied to the network where also throughput maximization is considered for the available eMBB users. That is obtained thanks to guaranteeing that the eMBB users receive minimum interference in occupied resources by URLLC users.

Let $\boldsymbol{A}$, which is a matrix of size $K \times M$, represents the status of the users' connection to RUs. If the user k is connected to RU m, we have $A(k, m) = 1$, otherwise $A(k, m) = 0$. $\mathcal{N} = \{1, \ldots, N\}$ is considered as the set of RBs, where the assigned RB n to k-th UE from a particular RU m ($A(k, m) = 1$) is denoted by indicator $b_{k,m,n}$ and will be equal to

$b_{k,m,n} = 1$ if being allocated, otherwise $b_{k,m,n} = 0$. $\Gamma_{k,m}$ is the set of RBs allocated to k-th user from RU m where $b_{k,m,n} = 1$ for each RB n and $L_{k,m}$ and $R_{k,m}$ are the corresponding latency and full-bandwidth throughput, respectively. The set of URLLC and eMBB users under a particular RU $m \in \mathcal{M}$ coverage is denoted by U_m.

The overall objective for URLLC users is to minimize the communication latency as

$$\underset{\boldsymbol{A},\boldsymbol{\Gamma}_{k,m}}{\arg\min}(L_{k,m}), \ \forall k_{\text{URLLC}} \tag{5.2}$$

where k_{URLLC} is a particular URLLC user. At the same time, the objective for the eMBB users is as

$$\underset{\boldsymbol{A},\boldsymbol{\Gamma}_{k,m}}{\arg\max}(R_{k,m}), \ \forall k_{\text{eMBB}} \tag{5.3}$$

where k_{eMBB} is a particular eMBB user.

Problems 5.2 and 5.3 are subject to:

$$C1 : \ A(k,m) \in \{0,1\}, \ \forall k = 1,...,K, \quad \forall m = 1,...,M$$

$$C2 : \sum_{k\in\mathcal{K}} \sum_{n\in\mathcal{N}} b_{k,m,n} \leq \ N_T, \quad \forall m = 1,...,M$$

$$C3 : \sum_{n\in\mathcal{N}} b_{k_{\text{URLLC}},m,n} = \ N_i, \ \forall k_{\text{URLLC}} \in \mathrm{U}_m, \ \ i = k_{\text{URLLC}}, \forall m = 1,...,M$$

where N_i, $N_i \leq N_T$ is the required number of RBs for a particular URLLC user associated with RU m, and N_T, $N_T \leq |\mathcal{N}|$ is the total number of available RBs for each particular RU m. The constraint C1 represents the binary value matrix $\boldsymbol{A}$. Constraint C2 is ensuring that the total number of allocated RBs per RU m does not exceed the total number of available RBs for each RU. According to constraint C3, each URLLC user will only be allocated the required number of RBs to receive URLLC packets. Problems (5.2) and (5.3) are non-linear integer complex problems which could be solved with exhaustive search with high complexity.

Assuming each user reports a CQI for S cells, the association will result in the complexity of $O((S+1)^{(K)})$. This is too high complexity for practical network implementations with a large number of URLLC users that need quick scheduling decisions in each TTI. Moreover, the complexity will be increased with RB allocation. Motivated by proposals from [74], this optimization will be performed through the solution of two sub-problems, namely, by a TD low complexity scheduler (optimized from the proposed TD scheduler in [74] to improve the latency performance of URLLC users) and a novel cooperative FD scheduler (to manage the interference when the number of users is large). URLLC payloads are scheduled initially in order to avoid extra latency. Therefore, eMBB users will be scheduled just after URLLC users. The applied scheme including TD and FD schedulers, which will be performed in sequence, is explained next. The high level view for the proposed RRM application is illustrated in Fig. 5.2.

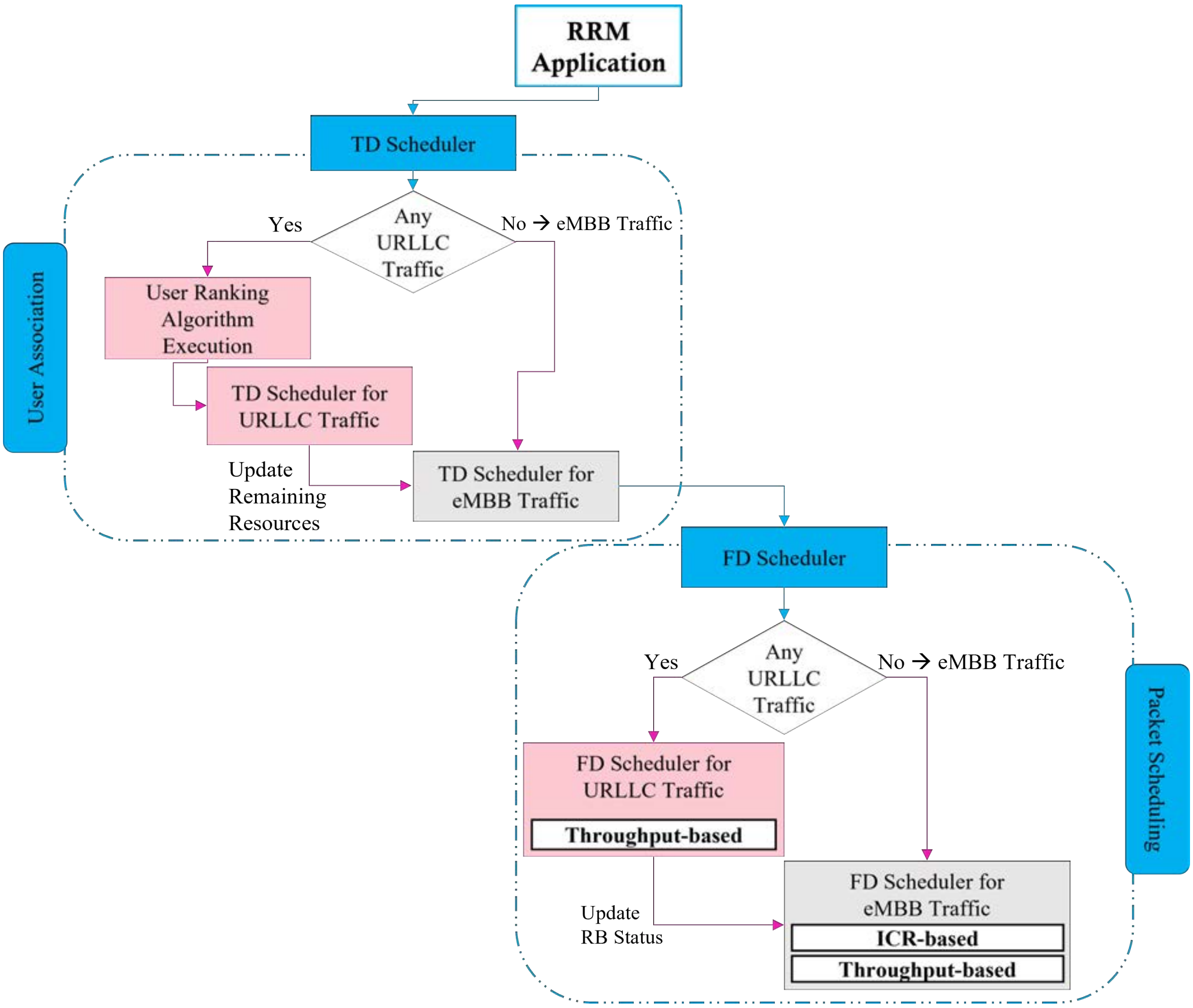


Figure 5.2: RRM Application high level view, including TD and FD schedulers.

5.2.2 User association

As we concentrate on low latency communication of high user-density scenarios with a large number of URLLC devices, the number of RBs is considered as a limiting factor which will cause extra delay for the users when they face a lack of RBs. Therefore, the number of occupying resources (N_i) will be taken into consideration when the TD scheduler associates URLLC users with RUs for the set of RBs.

HARQ retransmissions are scheduled from a RU allocating RBs with highest CQI in priority. Afterwards, new payloads will be scheduled. It is assumed that packets will be scheduled without segmentation. As the utility function for URLLC users follows the problem (5.2) and for eMBB users it follows (5.3), thus we separate the TD schedulers for each corresponding traffic group, as follows.

TD scheduler for URLLC users: We note that the user association metric $\tau_{k,m}$ for pairs of users and RUs for the TD scheduler in [74] includes latency and normalized full-bandwidth throughput for each user k served by any RU m. Building on that, in order to mitigate the RB limitation problem for a large number of URLLC users, we propose **Algorithm 1** for the ranking of users under each RU. Through this algorithm, rankings of users from RUs perspective regarding the RSRP of users averaged over bandwidth ($P_{r,\bar{n}}(k,m)$) will be stored in matrix $\boldsymbol{Q}$.

```
Algorithm 1: User Ranking Algorithm
  Input  : $\boldsymbol{Q} = [0]_{K\times M}$; Iq $= [0]_{K\times 1}$, $\mathcal{K}$; $\mathcal{M}$; $\boldsymbol{P_{r,\bar{n}}}$
  Output: $\boldsymbol{Q}$
for $m = 1 : M$ do
    $\mathbf{Iq}^* = \text{index}_k(\text{sort}\,(P_{r,\bar{n}}(:,m)))$, sort in descending order
    $Q(:,m) = \text{index}_k(\text{sort}(\mathbf{Iq}^*))$, sort in ascending order
end for
return $\boldsymbol{Q}$
```

It supports optimization problem (5.2) while satisfying constraints C3 for URLLC users. The association metric $\tau_{k,m}$ normalized with a correction ranking factor $Q_{k,m}$, is defined as

$$\tau_{k,m} = L_{k,m} + \frac{R_{k,m}}{0.5\ln(Q_{k,m})\sum_{m\in\mathcal{M}} R_{k,m}}. \tag{5.4}$$

The term $L_{k,m}$ is to prioritize users which are closer to the latency target. $R_{k,m}$ is for channel aware scheduling to decrease the HARQ probability. Moreover, the normalized ranking correction factor $0.5 \ln(Q_{k,m})$ will avoid extra resource occupation and provide an opportunity for a higher number of users to be scheduled by RUs. Normalizing through $\sum_{m \in \mathcal{M}} R_{k,m}$ gives lower priority to the users which have the possibility of being associated with other RUs.

TD scheduler for eMBB users: The user association metric m^* for eMBB users following (5.3) is targeted to maximize their throughput. Therefore, each eMBB user (k_{eMBB}) will be associated with the RU m^* which provides the highest wide-band CQI (i.e., highest RSRP $\boldsymbol{P_{r,\bar{n}}}$ for that particular eMBB user). It is worth to note that the eMBB users will be only scheduled if a particular RU m has remaining RBs after URLLC users allocation.

$$m^* = \arg\max_{m \in \mathcal{M}} (P_{r,\bar{n}}(k_{\text{eMBB}}, m)). \tag{5.5}$$

Considering the required number of RBs (N_i) per URLLC user and the available number of RBs per RU, the central RAN controller sequentially selects a pair (k, m) which has the highest metric $\tau_{k,m}$ and associates them if there are enough remaining RBs for the URLLC payload. All the remaining pairs corresponding to the selected users will be removed if the association is executed, otherwise, only that pair will be removed. The complexity of the proposed user association is $O(|\mathcal{M}|\,|\mathcal{K}| \log(|\mathcal{M}|\,|\mathcal{K}|))$ of the same order as [74]. After all the URLLC users are checked, the RAN controller will associate eMBB users with the RUs following the eMBB association metric, if there are still remaining RBs.

5.2.3 Resource Allocation

For URLLC traffic, a large number of URLLC users could cause a higher transmission delay for those UEs with lower SINR. For eMBB traffic, UEs will be scheduled with lower priority after URLLC traffic. Hence, a higher competition for RB allocation will worsen their performance. However, the design of an efficient resource allocation for such a large number of users will produce as a result that URLLC and eMBB UEs are being scheduled with the remaining RBs in a way that provides higher signal quality for them. Therefore, to support problems (5.2) and (5.3), we propose to use the following FD schedulers for URLLC and eMBB UEs, respectively. In the following, we propose an adaptation of previously existing schedulers in order to fulfil the requirements.

FD scheduler for URLLC users: FD scheduler for URLLC traffic is subjected to provide data transmission with high reliability for all UEs, even those having low SINR.

- Throughput-based [74]: RB n will be allocated to URLLC user k which has the highest metric of

  $$\hat{\Phi}_{k,n} = \arg\max_{n \in \mathcal{N}} \left(\frac{R_{k,m,n}}{R^{T}_{k,m}}\right) \tag{5.6}$$

  where $R_{k,m,n}$ and $R^{T}_{k,m} = \sum_{n \in \mathcal{N}} R_{k,m,n}$, represent the achievable throughput of RB n and the sum throughput of all RBs for user k, respectively.

  This allocation process will be continued until all URLLC users are allocated with their required number of RBs. Note that it was already verified in TD scheduler that each RU m has enough number of available RBs for its corresponding URLLC users.

FD scheduler for eMBB users: eMBB users will be scheduled through the FD scheduler with all the remaining RBs per RU m after URLLC users. However, the received interference is impacting their throughput. FD scheduler allocates RBs to them targeting on maximizing their achieved throughput. This could be performed with competitive RB allocation (Throughput-based) or cooperative RB allocation (ICR-based).

- Throughput-based: In this option the same FD scheduler as for URLLC users could potentially be used (for RB allocation), which means using (5.6).

- ICR-based: Motivated by the interference contribution ratio concept (ICR) [91], we propose ICR for RBs as the scheduling metric for eMBB users FD scheduler. Knowing sub-band CQI and channel measurements per RB at the central RAN controller, we define $P_{r,\bar{k}}(m, n)$ as average RSRP per RB from each RU m over associated users with that particular RU. Building on that, the interference received by the rest of the users in the network from allocating a RB n in particular RU m to its corresponding associated users is

$$I_{m,n} = \sum_{i \in \mathcal{M}, i \neq m} P_{r,\bar{k}}(i,n). \tag{5.7}$$

The FD scheduler allocates RB n to eMBB user k based on ICR metric for pairs of UEs and RBs that have the lowest metric of

$$\Phi_{k,n} = \underset{n \in \mathcal{N}}{\arg\min}\, (\lambda_{k,m,n}) \tag{5.8}$$

where $\lambda_{k,m,n}$ is defined as

$$\lambda_{k,m,n} = \frac{I_{m,n}}{A(k,m)P_r(k,m,n)}. \tag{5.9}$$

With the help of the proposed metric, eMBB UEs are allocated the RBs with the least interference contribution to the network.

The FD scheduler for eMBB users performs scheduling per RU m sequentially for pairs of users and RBs and will continue until no more RB remain in the corresponding RU. FD schedulers will remove the remaining pairs of allocated RB in each RU, in order to avoid reallocation of the same RB. As the result, eMBB users throughput will be optimized, which will be portrayed in the next section.

5.3 Performance Evaluation and Result Analysis

5.3.1 Simulation scenarios and parameters

For the simulation setup, we assume a network topology with 500 m inter-site distance (ISD) and the total number of RUs is $M = 6$, with 20 MHz bandwidth over a carrier frequency of 4 GHz. RU height is 25 m and UE height is 1.5 m. The maximum transmit power for RU m is set as 44 dBm and the RU and UE antenna gains are assumed to be 8 dB and 0 dB respectively. Sub-carrier spacing is considered 15 kHz and TTI size is 0.143 msec corresponding to 2 OFDM symbols mini-slot. The UEs are randomly deployed over the entire network and the total number of URLLC and eMBB users are 1500 and 30, respectively. FTP3 downlink traffic with payload size of $B = 200$ bytes and arrival rate of 166.33 [payload/sec/UE] is set for URLLC users. Full buffer traffic has been considered for eMBB users. The channel model is implemented based on a simplified version from the defined model mapped with the Urban Macro test environment, and associated path-loss models used in simulations are from [119]. The KPI is one-way latency with 99.999% reliability. Other related configurations are aligned with the system-level simulation parameters in [119].

5.3.2 Simulation results and analysis

In this section, we evaluate the proposed scheduling scheme and compare it against our implementation of the reference scheme [74] with centralized scheduling as the baseline. These schemes are implemented for scheduling eMBB users in addition to a large number of URLLC users.

- Proposed scheme:

  TD scheduler uses metric (5.4) normalizing by user ranking for URLLC users and metric (5.5) maximizing achievable throughput for eMBB users.

  FD scheduler considers RB ICR metric (5.6) for URLLC users. Either, RB Throughput-based metric (5.6) or ICR-based metric (5.8) are used for eMBB users.

- Reference scheme [74]:

  TD scheduler uses metric (5.4) without user ranking normalizing factor for URLLC users and metric (5.5) maximizing achievable throughput for eMBB users.

  FD scheduler considers the maximum throughput metric (5.6) for all users.

The complementary cumulative distribution function (CCDF) of the latency is depicted in Fig. 5.3. With the assumed payload size of $B = 200$ and high offered load where the number of URLLC users is large, the latency performance is affected by users competing to access resources. Thus, access to the required number of RB for the users that have the URLLC buffer payload in the particular TTI might not be possible and force them to stay in the queue. As the offered load increases, this delay becomes more critical.

It is observed in Fig. 5.3 that our proposed scheme provides significant gain in latency performance where there is a large number of URLLC users. At 10^{-5} outage, for the scenario where the number of users is 1200, our scheme has almost equivalent performance to the reference scheme with around 1.3 ms latency. In this scenario, HARQ occurs within $(10^{-1} - 10^{-3})$ percentile with the flat step in the simulation results. However, where the number of URLLC users is increased to 1500 UEs, there is a high competition to obtain the required number of RB by the users having packets in the buffer. The latency performance will be varying depending on the used scheduling policy. Our proposed scheme with 1.56 ms latency for the scenario with 1500 UEs outperforms the reference scheme which has 1.85 ms latency. This is equivalent to 29% latency reduction (closer to the target latency of 1 ms) for our proposed scheme. While, a HARQ has happened below 10^{-1} percentile with the flat step. This gain in latency is because of saving RB by our proposed scheme due to adding the normalizing factor of user ranking. Therefore, our scheme is able to give the scheduling priority to the users which require a lower number of RBs from a particular RU. Thanks to this, in the scenario with a large number of URLLC users which is our focus in this work, our scheduler is able to perfectly manage users' competition.

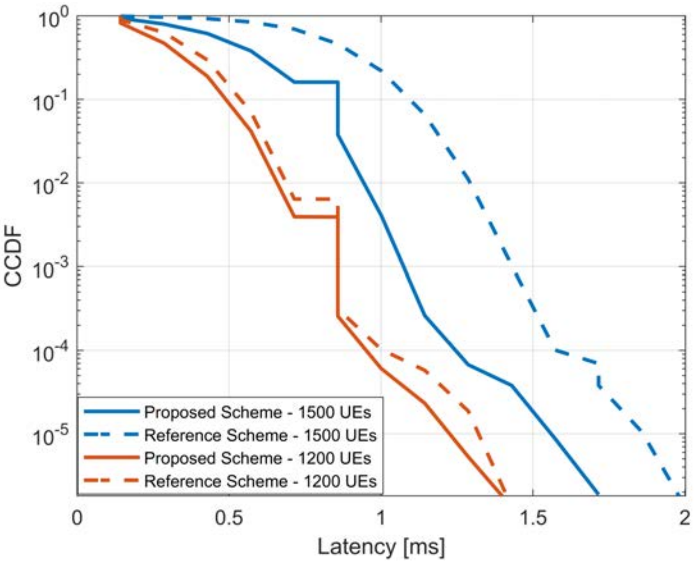


Figure 5.3: URLLC latency enhancement for different network scales with 1200 and 1500 URLLC Users.

Fig. 5.4 shows the impact of a high number of UEs on the transmission latency because of increasing the number of UEs that have to compete and wait for the available RB

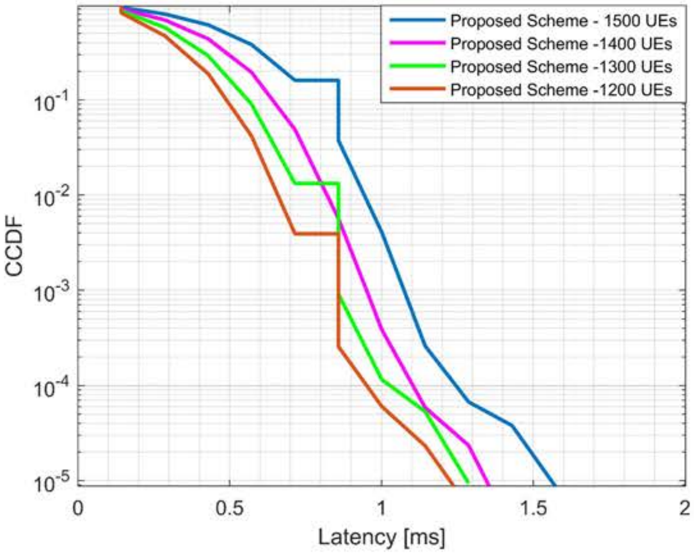


Figure 5.4: URLLC latency for different network scales with [1200 - 1500] URLLC Users.

to receive their buffered data. This is the reflection of the importance of RB saving during the RB scheduling on latency for URLLC users.

Fig. 5.5 plots the CDF of RB utilization per RU by URLLC users. It shows the advantage of our scheme in saving more RBs during user association through the TD scheduler. The less RBs being allocated to each of the URLLC users, the less delay will be pushed to other URLLC users because of lack of required RBs. As it is depicted in Fig. 5.5, the gain of our TD scheduler in saving RBs against the reference scheme is the same for both of the scenarios with 1200 and 1500 UEs. However, as it was shown in Fig. 5.3, the result of this saving in latency performance is dominant when the number of UEs increased and competition over available RBs appeared.

Thanks to our proposed TD scheduler, which supports the network with enhanced RB utilization through the efficient user association, more RBs will remain for eMBB users. However, it is expected that throughput performance of URLLC users will also be enhanced because of the proposed UE-RU association technique which includes the channel awareness factor in TD scheduling metric (5.4).

Fig. 5.6 depicts CDF of the network throughput for URLLC users. We can see that our proposed scheme outperforms the reference scheduler. This is because of the user ranking factor which increases the strength of channel awareness in the UE-RU association.

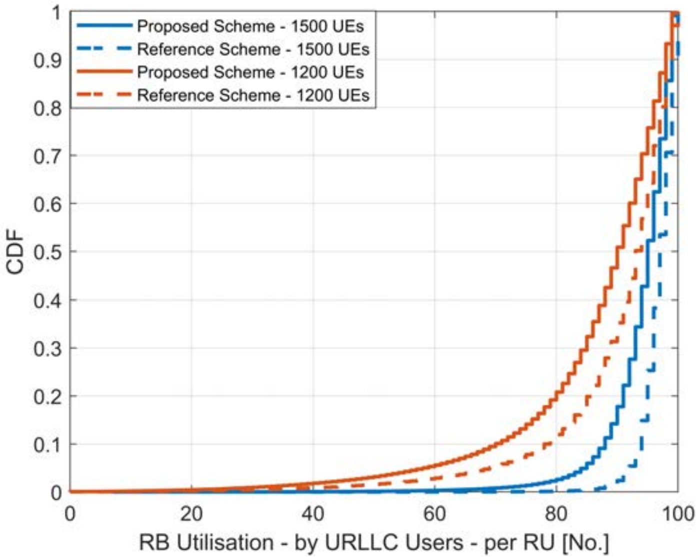


Figure 5.5: CDF of RB Utilization by URLLC Users per RU for different network scales with 1500 and 1200 URLLC Users.

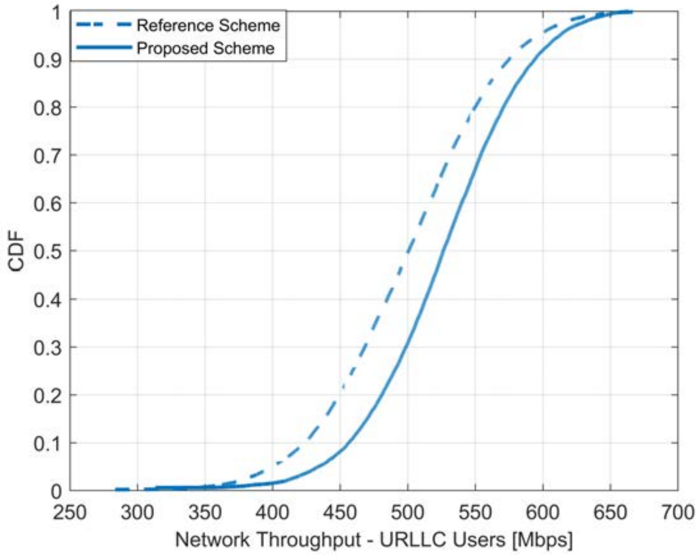


Figure 5.6: CDF of network throughput for 1500 URLLC Users.

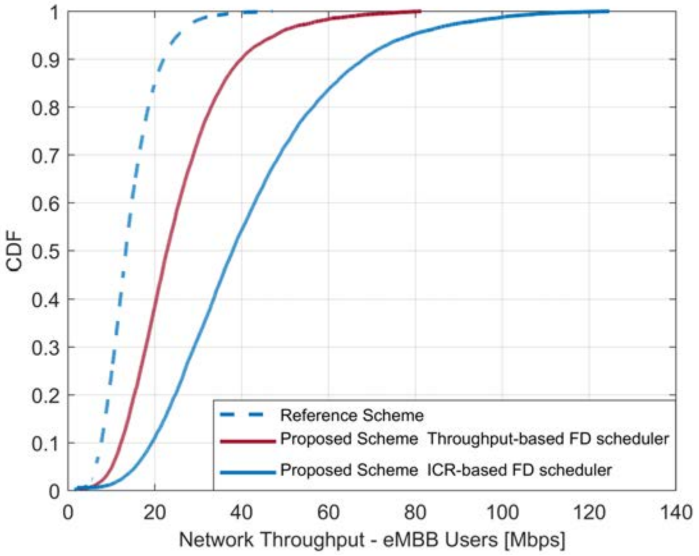


Figure 5.7: CDF of network throughput for scheduled eMBB Users.

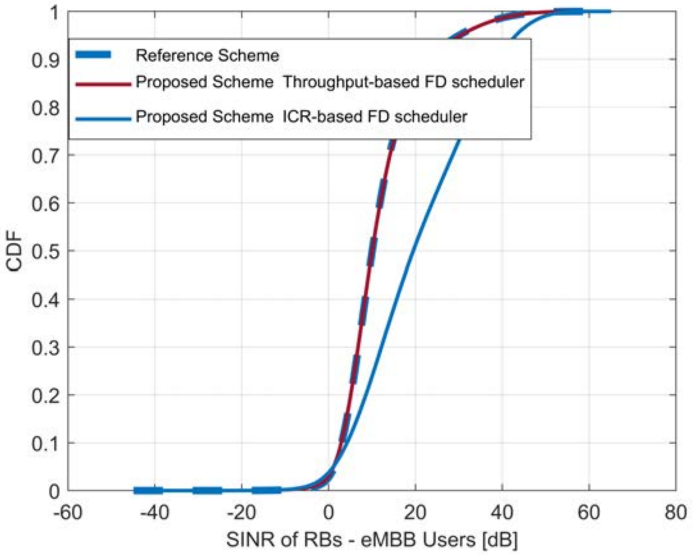


Figure 5.8: CDF of SINR of RBs for scheduled eMBB Users.

Fig. 5.7 shows the CDF of network throughput for eMBB users. It can be seen that our proposed scheme with ICR-based FD scheduler has higher gain in network throughput for eMBB users as compared to our proposed scheme with Throughput-based FD scheduler and our implementation of the reference scheme. The throughput enhancement happens because of two reasons. It is partly obtained by allocating a larger portion of bandwidth to the eMBB UEs because of saved RBs as the advantage of TD scheduler used for URLLC traffic. The improvement level due to this cause is shown in our proposed scheme with both ICR-based and Throughput-based scheduler. However, the extra throughput optimization is achieved through an optimized SINR level because of the efficient RRM (i.e., our proposed cooperative ICR-based FD scheduler).

The CDF of SINR of RBs for the scheduled eMBB UEs is presented in Fig. 5.8. The proposed scheme with ICR-based FD scheduler outperforms the proposed scheme with Through-based FD scheduler and the reference scheme. Our proposed efficient RB scheduling through ICR-based scheduler manages interference through allocation of RBs providing a stronger signal compared to their interference contribution in the SINR of UEs served by other RUs. However, it is worth to note that SINR performance of the proposed scheme with Throughput-based FD scheduler has almost the same performance as the reference scheme because of the competitive approach of RB allocation.

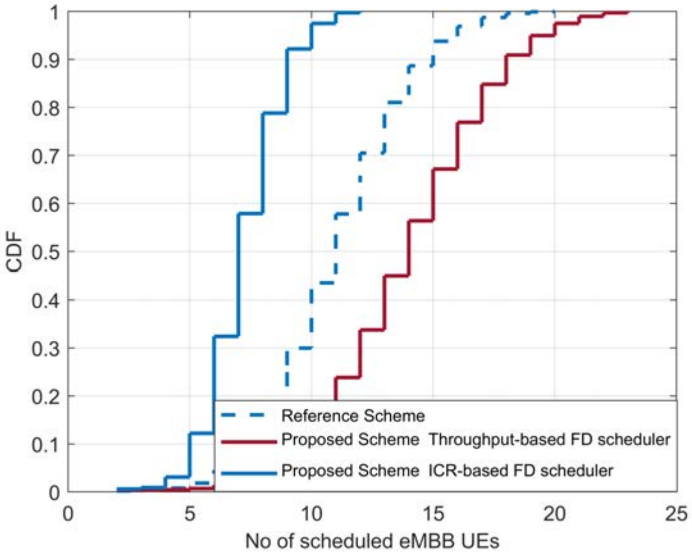


Figure 5.9: CDF of number of scheduled eMBB Users.

In contrast, the simulation results in Fig. 5.9 shows that the number of scheduled eMBB UEs (out of 30 dropped UEs in the network) is larger for the proposed scheme with the Throughput-based FD scheduler for eMBB traffic. This is because of the competitive allocation of this scheduler, which is not managing each UE's allocation impact when admitting it to the network. Whereas, cooperative ICR-based FD scheduler does admit eMBB UEs only if admitting them will not drop existing UEs' performance. Therefore, it is able to schedule a higher number of eMBB UEs at the cost of higher competition and larger network performance degradation. This proves the positive impact of the cooperative scheduler even for a small number of users in the cell-less RAN architecture. It is also shown that our proposed TD scheduler provides the possibility of scheduling more eMBB UEs because of less allocated RBs for URLLC traffic. Hence, depending on the expected KPI from the schedulers (i.e., based on the network throughput or number of scheduled eMBB UEs) the target FD scheduler could be activated for eMBB traffic. As it is shown in Fig. 5.8, our proposed scheme has almost on average 90% SINR level improvement over allocated RBs to the scheduled eMBB users. This is a significant contribution for the networks with resource limitations for eMBB users as a result of cooperative scheduling. Moreover, Fig. 5.9 shows the opportunity for a number of eMBB UEs to be scheduled around 27% larger as compared to legacy schemes because of saving RBs from the scheduling phase of URLLC traffic. This gives operators the flexibility for decision making about the selection of FD scheduler in URLLC-eMBB traffic coexistence scenarios.

5.4 Concluding Remarks

In this chapter, an enhanced RRM scheme was proposed to handle a mixed URLLC and eMBB traffic for 5G and beyond cell-less RAN. The proposed scheme managed the RB utilization through an efficient user association to decrease the one-way latency for URLLC users. It also managed interference through a novel ICR-based resource allocation technique, which resulted in enhancing the throughput of eMBB users. Considering the latency for URLLC users and network throughput for eMBB users as the main objective functions, two customized TD and FD schedulers are designed within the proposed RRM scheme. Simulation results showed that the proposed procedures provided a significant contribution for the scenarios with a large number of URLLC users in the network. Next chapter will investigate the energy efficiency issue of the cell-less RAN architecture.

Chapter 6

Energy Efficiency Enhancement for Cell-less architecture

In 5G and beyond 5G networks, the new cell-less radio access network architecture is adopted to overcome the extreme system capacity challenges generated by massive wireless devices used for diverse scenarios and various applications. At the same time, the evolution of mobile communications faces the important challenge of increased network power consumption. To fulfill user demands for various user densities and meanwhile reduce the power consumption, a novel energy-efficiency enhancement scheme, i.e., $(3 \times E)$ is presented in this chapter to increase the transmission rate per energy unit, with stable performance within the cell-less RAN architecture. The proposed $(3{\times}E)$ scheme activates two-step sleep modes (i.e., certain phase and conditional phase) through the intelligent interference management for temporarily switching APs to sleep, optimizing the network EE in highly loaded scenarios, as well as in scenarios with lower load. An intelligent control over underutilized/unused APs is considered, taking their interference contribution into account as the primary main criteria in addition to load-based conditional criteria. Therefore, our proposed scheme assures a stable performance enhancement and maintains an efficient power saving when the number of UEs increases, improving existing works not addressing this performance stability in peak-traffic hours. Simulation results show that the network EE is improved up to 30% compared to the reference algorithm and up to 60% with respect to the baseline algorithm in which all APs are active all the time. This content of this research is published as a research article [11] in IEEE Access.

The rest of the chapter is organized as: Section 6.1 presents the high-level architectural view of a cell-less RAN and corresponding system model. Section 6.2 formulates the problem mathematically and also proposes an $(3 \times E)$ scheme; Section 6.3 evaluates the performance and shows the results. Section 6.4 finishes the chapter with some concluding remarks.

6.1 System Model

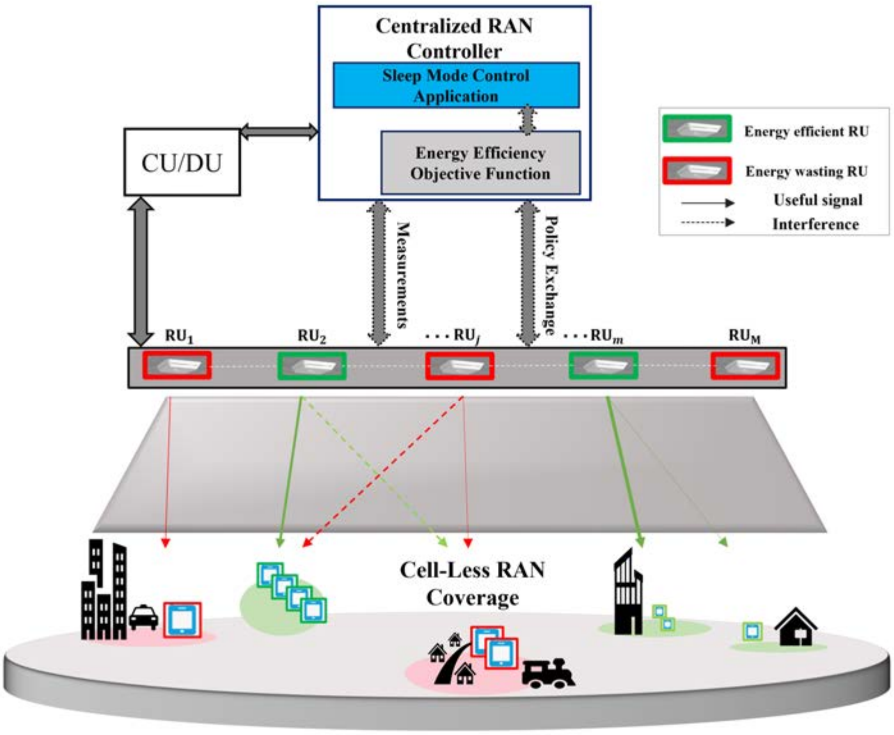


Figure 6.1: High level architectural view of a cell-less RAN.

We assume a cell-less architecture of the RAN for a dense scenario depicted in Fig. 6.1. In the following, the channel gain between user $k \in \mathcal{K}$ and RU m is $h_{m,k}$ including pathloss and shadowing effects. P^m is the transmission power of RU m and σ^2 is the additive white Gaussian noise power at each receiver. The SINR for the k-th user served by RU m in the downlink (RU to UE) is denoted by $\gamma_{m,k}$. Considering μ_m as the sleep mode indicator, which is representing RU in sleep mode if $\mu_m = 1$, and in active mode if $\mu_m = 0$, the SINR in the downlink $\gamma_{m,k}$ can be written as

$$\gamma_{m,k} = \frac{(1-\mu_m)P^m \left|h_{m,k}\right|^2}{\sum_{j\neq m, j\in\mathcal{M}} (1-\mu_j)P^j \left|h_{j,k}\right|^2 + \sigma^2}. \tag{6.1}$$

Aggregating the throughput per RB[3] of the set of users that are served by RU m, that is the set U_m, denoted by $R_{m,i_{\text{RB}}}$, the total throughput of the particular RU m can be obtained as [91]

$$R_m = \sum_{i\in U_m} N_i \, R_{m,i_{\text{RB}}} \tag{6.2}$$

where N_i is the minimum required number of RBs for a particular user.

According to the EARTH power model [124], the total consumed power P^m_{Total} is the summation of circuit power and transmit power (i.e., $P^m_{\text{Total}} = P^m_{\text{cir}} + \alpha P^m_{\text{out}}$) while the transmit power P_{out} would be limited to the maximum power at full load. α, P_{out}, ρ_m, and N_T represent the power amplifier efficiency, transmission power, load for a particular RU m, and the total number of RBs. The transmitted power can be written as

$$P^m_{\text{out}} = \rho_m P^m_{\text{max}} \tag{6.3}$$

$$\rho_m = \frac{\sum_{i\in U_m} N_i}{N_T}. \tag{6.4}$$

As the major source of power consumption is the circuit power of an active RU, through switching a RU to the sleep mode with zero transmission power, much lower circuit power could be consumed. The circuit power can be measured as

$$P_{\text{cir}} = (1-\mu)P^{\text{active}}_{\text{cir}} + \mu \, P^{\text{sleep}}_{\text{cir}} \tag{6.5}$$

while we consider $P^{\text{active}}_{\text{cir}}$ and $P^{\text{sleep}}_{\text{cir}}$ as circuit power for active and sleep RU respectively. The total network EE can be calculated as the aggregation of the RUs throughput divided by the total network power consumption, namely

$$EE_{\text{Total}} = \frac{\sum_{m\in\mathcal{M}} R_m}{\sum_{m\in\mathcal{M}} P^m_{\text{Total}}}. \tag{6.6}$$

---

[3] A resource block is the smallest unit of resources that can be allocated to a user.

6.2 Problem Formulation and Proposed Energy-Efficiency Enhancement $(3 \times E)$ Scheme

6.2.1 Problem Formulation

Let $\boldsymbol{A}$, which is a matrix of size $K \times M$, represents the status of the users' connection to RUs. If $\mu_m = 0$ and the user k is connected to RU m, we have $A(k, m) = 1$, otherwise $A(k, m) = 0$. In order to find the efficient dynamic user association to the cell-less RAN and deciding to switch inefficient RUs in sleep mode that maximize the network EE, the optimization problem can be expressed as

$$\boldsymbol{A}^* = \arg\max_{\boldsymbol{A}}(EE_{\text{Total}}) \tag{6.7}$$

Subject to:

$$C1:\ A(k,m) \in \{0,1\},\ \ \forall k = 1,...,K,\ \ \ \forall m = 1,...,M$$

$$C2:\ \sum_{j \in \mathcal{M}} R_j \geq\ ((1-\beta)\sum_{j \in \mathcal{M}} R_j^{\text{baseline}})$$

$$C3:\ \sum_{k \in \mathcal{K}} A(k,m)\ \leq\ N_T,\quad \forall m = 1,...,M$$

$$C4:\ \sum_{m \in \mathcal{M}} A(k,m)\ \leq\ 1,\qquad \forall k = 1,...,K$$

$$C5:\ \ R_k = N_k\, R_{m,k_{\text{RB}}} >\ R_{k_{\min}},\quad \forall k = 1,...,K$$

$$C6:\ \min(EE_j = \frac{R_j}{P^j_{\text{Total}}}) \geq \min(EE_m),\quad \forall j \in M^{\text{temp}}_{\text{active}},\quad \forall m \in M_{\text{active}}$$

$$C7:\ \ P^m_{\text{out}} \leq P^m_{\max},\ \ \forall m = 1,...,M$$

The constraint C1 represents the binary value matrix $\boldsymbol{A}$. Constraint C2 is ensuring that the network throughput does not suffer a big loss (considering R_j^{baseline} as the total

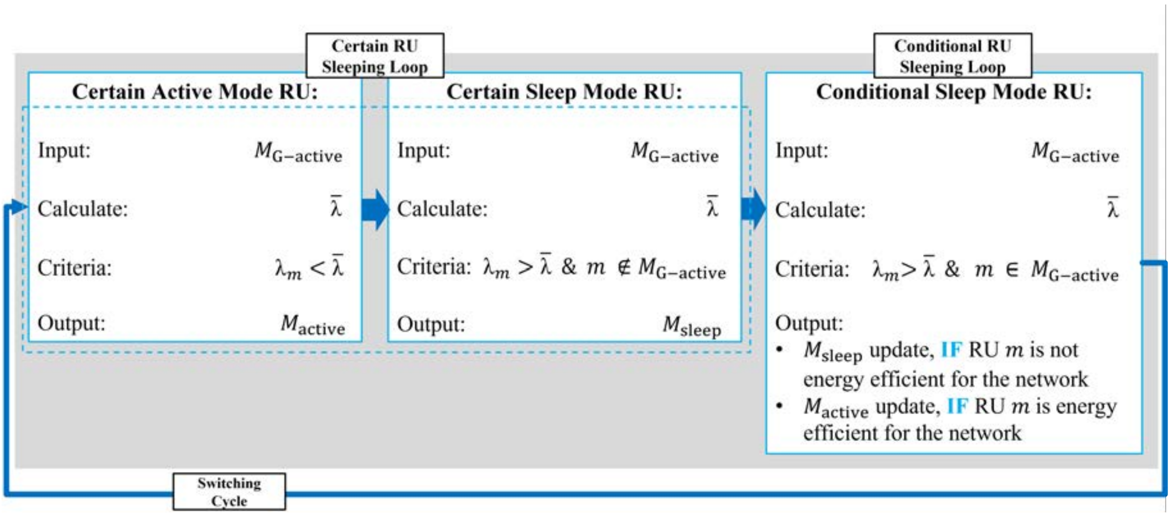


Figure 6.2: High level view of the proposed $(3 \times E)$ scheme.

throughput of a particular RU j before applying our sleep mode technique on the system and β as the allowed traffic loss ratio, which is configurable based on network conditions and operator preferences). According to constraints C3 and C4, each RU can use up to a maximum number of available RBs and each UE may be served by maximum one RU, respectively. Constraint C5 ensures that the required throughput of each UE is achieved, where $R_{k_{\min}}$ denotes the minimum required throughput for user k. Constraint C6 (assuming $M^{\text{temp}}_{\text{active}}$ as the temporary RU active set where $M^{\text{temp}}_{\text{active}} = M_{\text{active}} \cup \{\text{RU } j\}$ to include RU j temporary) ensures that the number of transmissions per energy unit will be increased along with saving the energy consumption. Finally, the constraint C7 will keep the transmission power limited to a maximum transmission power of any particular antenna.

The aim is to enhance the EE through the choice of the active and sleep sets of RUs including UE-RU association. The optimal solution could be found through an exhaustive search, which is not time and computationally efficient. Hence, we propose a scheme which enhances the EE ending up with a near optimal solution as it is shown in the performance evaluation section. In this work, the customized RU sleep mode selection solution will consider the interference that each RU is causing to the network in comparison to its provided useful signal. Therefore, the interference ratio parameter in the downlink is defined as follows, which is adapted from the interference contribution ratio (ICR) concept [91]

$$\lambda_m = \frac{\sum_{i \notin U_m} P^m \left|h_{m,i}\right|^2}{\sum_{i \in U_m} P^m \left|h_{m,i}\right|^2}. \tag{6.8}$$

The higher ICR a particular RU has, the lower useful signal it provides toward the network. However, the higher ICR will reflect propagating more interference to the network. Therefore, the RU will cause the entire network transmission performance to be degraded. In this case, such active RU will be considered as energy wasting and the cell-less network could gain more by saving energy consumption through making it sleep. Therefore, users' radio conditions improve thanks to interference mitigation.

6.2.2 Proposed $(3 \times E)$ Scheme

This thesis proposes an energy-efficient UE-RU association with the possibility of making inefficient RUs sleep. It contains two phases: (i) initial UE-RU association, (ii) RU sleep mode selection. As it is addressed in [92], using the RU sleep mode selection considering load, RSRP[4] of serving UEs and interference, could reduce the power consumption and enhance throughput.

Initial UE-RU association: In the first step, the initial association will be executed with the link providing the highest RSRP $P_r(k,m)$ for each user k from a particular RU m in the network. In the cell-less network, this information can be obtained at the central RAN controller thanks to the information that UEs periodically feedback. The pseudocode of user association is mentioned in **Algorithm 2**.

Algorithm 2: The initial UE-RU association phase of sleep mode proposed technique

```
Input  : $A = [0]_{K \times M}$; $\mathcal{K}$; $\mathcal{M}$; $P_r$
Output: $A$
for $i = 1 : K$ do
    $m^* = \arg\max_{A}(P_r(i,m))$
    $A(i,m^*) = 1$
end for
return $A$
```

RU sleep mode selection: The sleep mode control application will execute the $(3 \times E)$ scheme in a cooperative manner (i.e., considering a set of RU's conditions and constraints) thanks to the central RAN controller support.

---

[4] The RSRP is defined as "linear average over the power contributions (in Watts) of the resource elements that carry cell-specific reference signals within the considered measurement frequency bandwidth [125]".

The proposed $(3 \times E)$ RU sleep mode selection scheme would dynamically update the association and sleep RUs set considering the latest network states; this result could be used within any particular scheduling time. In this work each cycle is performed under two separate loops, denoted as a certain and conditional RU sleeping loop. The high level view of the proposed $(3 \times E)$ scheme is portrayed in Fig. 6.2.

Let us define $M_{\text{G-active}}$ as the set of RUs satisfying

$$\max(RSRP_j) > \ RSRP_{\text{thr}} \quad \text{or}\, \rho_j > \rho_{\text{th}} \tag{6.9}$$

where $\max(RSRP_j) = \max(P^j \left|h_{j,i}\right|^2)$, $i \in U_j$. $RSRP_{\text{thr}} = 5\ \min(RSRP_j)$ and $\rho_{\text{th}} = 0.5\ N_T$ [92] represent network RSRP and load thresholds, respectively. The set $M_{\text{G-active}}$ satisfies that $||M_{\text{G-active}}||_0 = L$ ($||.||_0$ indicates the set cardinality). Given $M_{\text{G-active}}$, average ICR parameter $\overline{\lambda}$ can be obtained as

$$\overline{\lambda} = \frac{\sum_{j \in M_{\text{G-active}}} \lambda_j}{L}. \tag{6.10}$$

In the first stage, the certain RU sleeping loop determines the certain active mode RU and certain sleep mode RU sets, that is, the RUs that will surely be either active or put to sleep, respectively.

- **Certain Active Mode RU:** M_{active} set formed by each particular RU m satisfying

$$\lambda_m < \ \overline{\lambda},\ m \in \mathcal{M}. \tag{6.11}$$

- **Certain Sleep Mode RU:** M_{sleep} set formed by each particular RU $m \notin M_{\text{G-active}}$ satisfying

$$\lambda_m > \ \overline{\lambda}. \tag{6.12}$$

  Now, in a second stage, some RUs will be conditionally considered to be either active or asleep, as follows:

- **Conditional Sleep Mode RU:** In this loop, each particular RU $j \in M_{\text{G-active}}$, will be included in $M_{\text{active}}^{\text{temp}}$ set temporary if it satisfies that

$$\lambda_j > \overline{\lambda}. \tag{6.13}$$

Each RU $\in M_{\text{active}}^{\text{temp}}$ would be included in M_{active} set permanently if satisfying (6.14) and (6.15) conditions. Otherwise, it would be included in M_{sleep} set permanently.

$$\min(EE_j) > \min(EE_m), \;\; j \in M_{\text{active}}^{\text{temp}}, m \in M_{\text{active}}. \tag{6.14}$$

$$\frac{\sum_j R_j}{\sum_j P_{\text{Total}}^{j}} > \frac{\sum_m R_m}{\sum_m P_{\text{Total}}^{m}}, \;\; j \in M_{\text{active}}^{\text{temp}}, m \in M_{\text{active}}. \tag{6.15}$$

Algorithm 3 shows the details of the proposed $(3 \times E)$ RU sleep mode selection scheme. Separating the loops in order to have a conditional interference management, apart from a certain sleeping loop, would give the higher level of enhancement of network EE in the lower populated interfering scenarios. The conditional sleeping loop enhances the power saving and increases the transmission rate per energy unit, which is shown in the performance evaluation section. These efficient steps to enhance the EE (i.e., activation/deactivation process to separate loops and conditional interference management) are beyond the available reviewed works such as [91], [92]. While satisfying constraint C2, the proposed $(3 \times E)$ RU sleep mode selection scheme is performed continuously (each iteration is denoted as switching cycle) along time in the cell-less network. This process updates the UE-RU association and the RU sets dynamically and based on the latest status of the RUs to reach a near optimal and network energy-efficient association. The entire flow diagram of the proposed algorithm is illustrated in Fig. 6.3.

In the proposed scheme, the maximum number of iterations required for the certain RU sleeping loop is $|\mathcal{M}|\,|\mathcal{K}|$ and the maximum number of iterations required for the conditional RU sleeping loop is $|\mathcal{M}|\,|\mathcal{K}|$. Therefore, the maximum number of iterations for **Algorithm 3** is $(2\,|\mathcal{M}|\,|\mathcal{K}|)$. Hence, the asymptotic complexity of our proposed algorithm is of $O(|\mathcal{M}|\,|\mathcal{K}|)$. Even though the computational complexity is not reported in [91] and [92], we found a linear complexity of the same order when implementing them.

Algorithm 3: Proposed $(3 \times E)$ RU sleep mode selection scheme

```
   Input  : $A$; $R_{k_{\min}}, k \in \mathcal{K}$; $N_T$; $RSRP_j, \rho_j, j \in \mathcal{M}$; $RSRP_{\text{thr}}$; $\rho_{\text{th}}$; $M_{\text{G-active}} = [\ ]$;
            $M_{\text{active}} = [\ ]$; $M_{\text{sleep}} = [\ ]$; $\beta$
   Output: $M_{\text{sleep}}$; $M_{\text{active}}$; Updated $\boldsymbol{A}$
 1 Obtain Network baseline throughput $R^{\text{baseline}}_{\text{Total}} = \sum_{j \in M} R^{\text{baseline}}_j$ by (6.2)
 2 Calculate $EE_{\text{Total}}$ by (6.6) using (6.2)
 3 for each RU $j \in \mathcal{M}$ set do
 4     if RU $j$ satisfies (6.9) then
 5         $M_{\text{G-active}} \leftarrow$ RU $j$
 6     end if
 7 end for
 8 Calculate $\overline{\lambda}$ by (6.10) given $M_{\text{G-active}}$
 9 for each RU $j \in \mathcal{M}$ set do
10     if RU $j$ satisfies (6.11) then
11         $M_{\text{active}} \leftarrow$ RU $j$
12     end if
13 end for
14 for each RU $j \notin M_{\text{G-active}}$ do
15     if RU $j$ satisfies (6.12) then
16         $M_{\text{sleep}} \leftarrow$ RU $j$
17     end if
18 end for
19 Find set of UEs not assigned to any RU $j \in M_{\text{active}}$ as un-defined UE set $\mathcal{K}_{\text{UD}}$
20 for each UE $i \in \mathcal{K}_{\text{UD}}$ and RU $j \in M_{\text{active}}$ do
21     Repeat Algorithm 1
22     Update $A$
23 end for
24 for each RU $j \in M_{\text{G-active}}$ do
25     if RU $j$ satisfies (6.13) then
26         if RU $j$ satisfies (6.14) and (6.15) then
27             $M_{\text{active}} \leftarrow$ RU $j$
28         else
29             $M_{\text{sleep}} \leftarrow$ RU $j$
30         end if
31     end if
32 end for
33 Update $\mathcal{K}_{\text{UD}}$
34 Go to (Repeat step 19:23)
35 Calculate Network throughput $R_{\text{Total}} = \sum_{j \in M_{\text{active}}} R_j$ by (6.2)
36 if $R_{\text{Total}} \geq (1-\beta) \times R^{\text{baseline}}_{\text{Total}}$ then
37     Go to next switching cycle (Repeat step 2:35)
38 end if
```

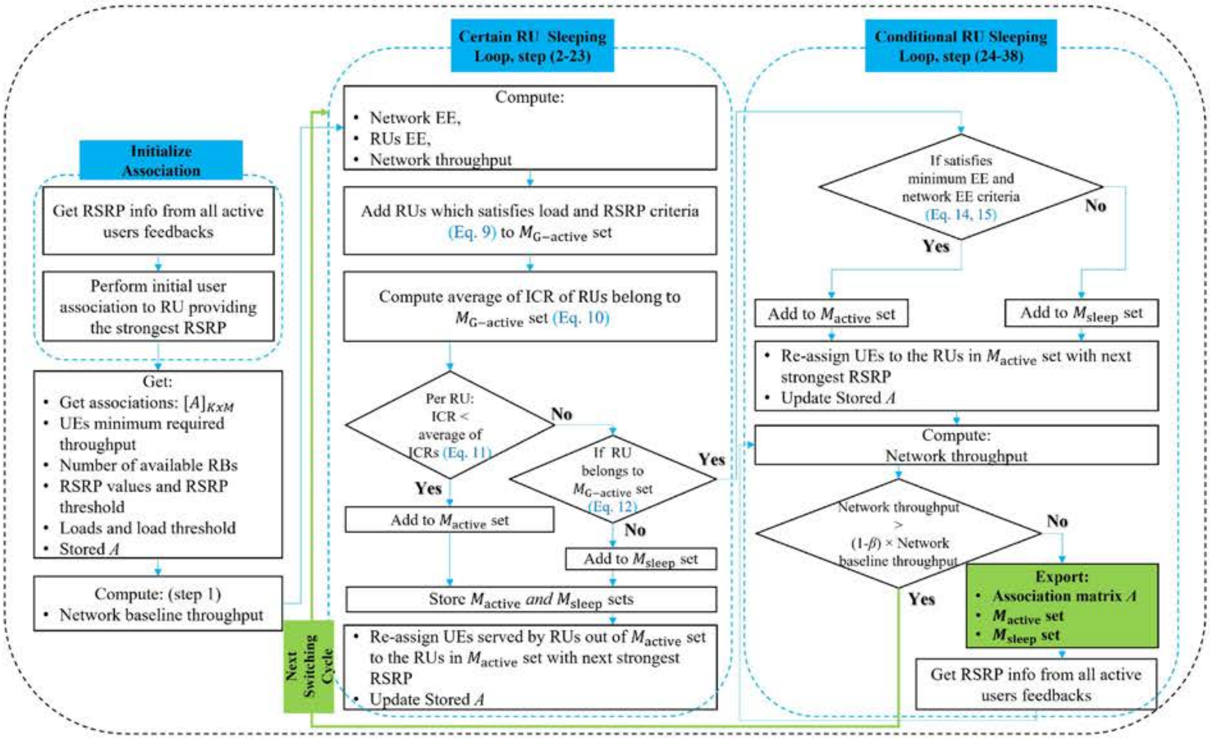


Figure 6.3: Flow diagram of the $(3 \times E)$ RU sleep mode selection scheme within Cell-Less RAN Architecture.

6.3 Performance Evaluation and Result Analysis

6.3.1 Simulation scenarios and parameters

In our simulation setup of a cell-less architecture, we assume a hexagonal network topology with 150 m inter site distance (ISD), with 20 MHz bandwidth over a carrier frequency of 4 GHz. In addition, we also consider a Voronoi RU deployment scenario for the results shown in Fig. 6.5, where the locations of RUs follow a Poisson point distribution with the same minimum distance of RUs as in the hexagonal topology scenario. This scenario is used for the sake of comparison, to check whether the RU distribution has an impact on the performance. All other simulation parameters remain the same for both hexagonal and Voronoi topology. RU height is 3 m and UE height is 1.5 m. The RU and UE antenna gains are assumed to be 5 dB and 0 dB respectively. The required UE throughput is considered as 1 Mbps for all users. The UEs are randomly deployed over the entire network. We consider the power consumption parameters from [124] to calculate EE. The maximum transmit power for RU m is set as 0.13 W, with setting 6.8 W and 4.3 W for the circuit power in active and sleep mode respectively. The channel model is implemented based on a simplified version from the defined model in Annex 1 in [119] mapped with the Indoor Hotspot-eMBB test environment, and the path-loss models used in simulations are from Table A1-2 in Annex 1 in [119],

$$PL_{\text{InH-Los}} = 16.9\log_{10}(d_{3D}) + 32.8 + 20\log_{10}(f_c) \tag{6.16}$$

$$PL_{\text{InH-NLos}} = 43.3\log_{10}(d_{3D}) + 11.5 + 20\log_{10}(f_c) \tag{6.17}$$

where d_{3D} is the distance between the transmitter and receiver in meters and f_c is carrier frequency in GHz. Other related configurations are aligned with the system-level simulation parameters in [119].

6.3.2 Simulation results and analysis

In this section, we evaluate the following schemes and compare their performance:

- Baseline Algorithm: This performs the best cell (strongest link) UE-RU association without any sleep mode scheme.
- EE Algorithm - Reference: The sleeping scheme is based on [92].
- EE Algorithm - Non-conditional ($3 \times E$) scheme: This sleeping scheme performs as described in 6.2.2, while it will not check the conditions (6.14) and (6.15). The candidate RUs of the conditional loop entirely would be included in M_{sleep} set. The switching cycle is executed only once per TTI.
- EE Algorithm - Conditional ($3 \times E$) scheme: This is the scheme as described in 6.2.2 with a switching cycle executed only once per TTI.
- EE Algorithm - Proposed ($3 \times E$) scheme: This is the proposed scheme as described in 6.2.2. The algorithm switching cycle will be continued while satisfying C2 from (6.7), where we have configured $\beta = 4\%$.

Fig. 6.4 depicts the gap in the obtained network EE between the proposed ($3 \times E$) RU sleep mode selection or the benchmark schemes and the exhaustive search algorithm. As exhaustive search is a time consuming and complex technique to achieve the optimal solution, the simulation is performed in small scale scenarios for up to 6 RUs serving 3 UEs. To have a fair comparison, C2 and C6 constraints are excluded from all the implemented schemes in this simulation.

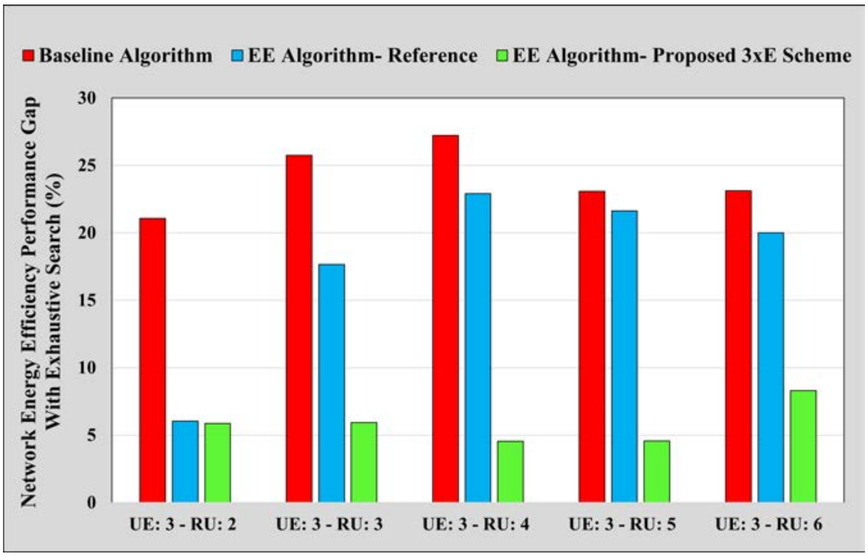


Figure 6.4: Network EE gap with respect to Exhaustive Search.

For the very small scale scenario of 2 RUs and 3 UEs, as there is only the possibility of sleeping 1 RU, no performance difference is observed between the reference algorithm and our proposal scheme. This performance enhancement for the proposed $(3 \times E)$ RU sleep mode selection scheme is more noticeable in higher RU scale scenarios that provide more options of sleeping mode candidate RUs. Simulation results show that the proposed scheme achieves the lowest network EE performance gap with respect to exhaustive search with an average gap around 6%. The baseline algorithm without any sleep mode scheme has the highest gap and the reference algorithm is achieving lower performance than the proposed one. It is important to remark that these results correspond to simplified scenarios where the exhaustive search is feasible, while the performance of the proposed scheme improves in larger scenarios, as discussed. Then, it is foreseen that this gap would be even lower for a higher number of RUs, although it cannot be practically estimated.

The conditional RU sleeping loop benefit is illustrated in Fig. 6.5 with Voronoi RU deployment and Fig. 6.6 with hexagonal RU deployment that shows the CDF of network EE enhancement of different options for 150 RUs and 150 UEs. The Voronoi deployment has been implemented just to have an initial comparison with a random deployment of RUs. However, it is shown that the performance of the algorithms is similar with both deploy-

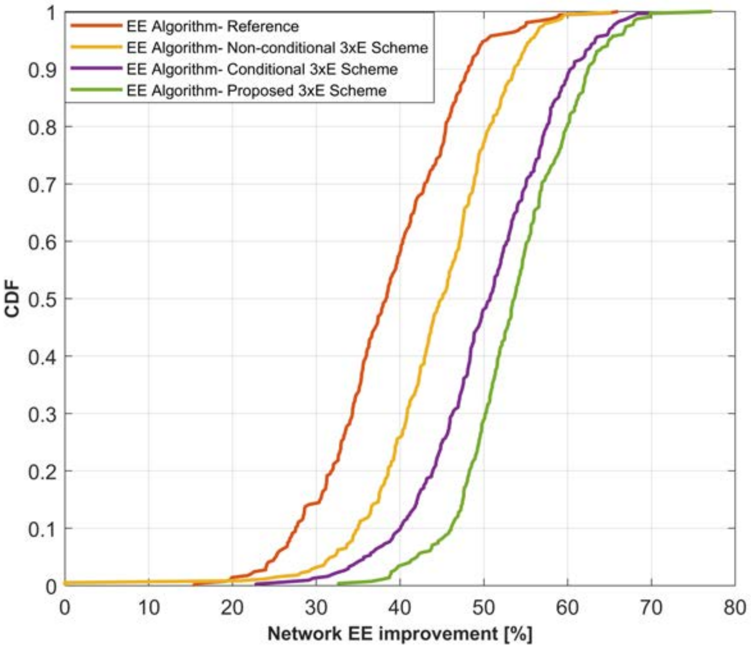


Figure 6.5: Network EE improvement over baseline with Voronoi RU deployment.

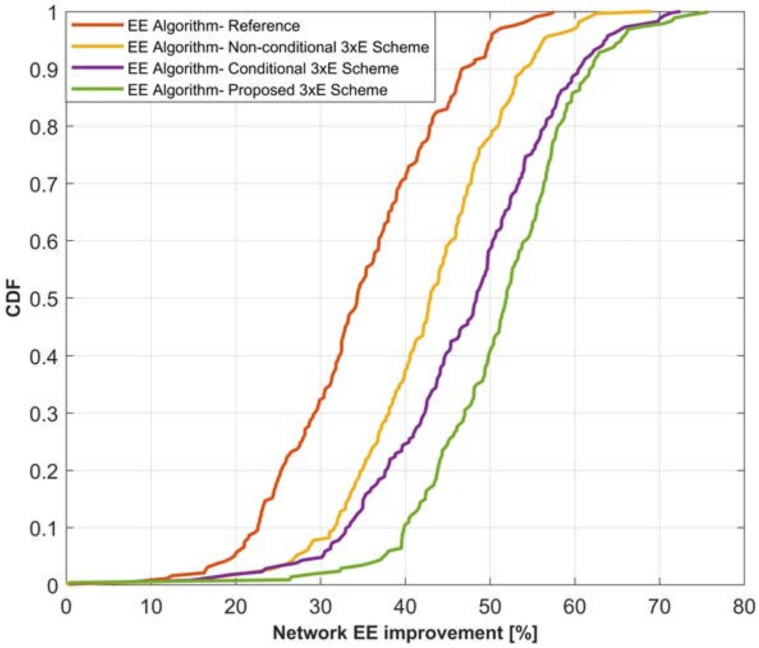


Figure 6.6: Network EE improvement over baseline with hexagonal RU deployment.

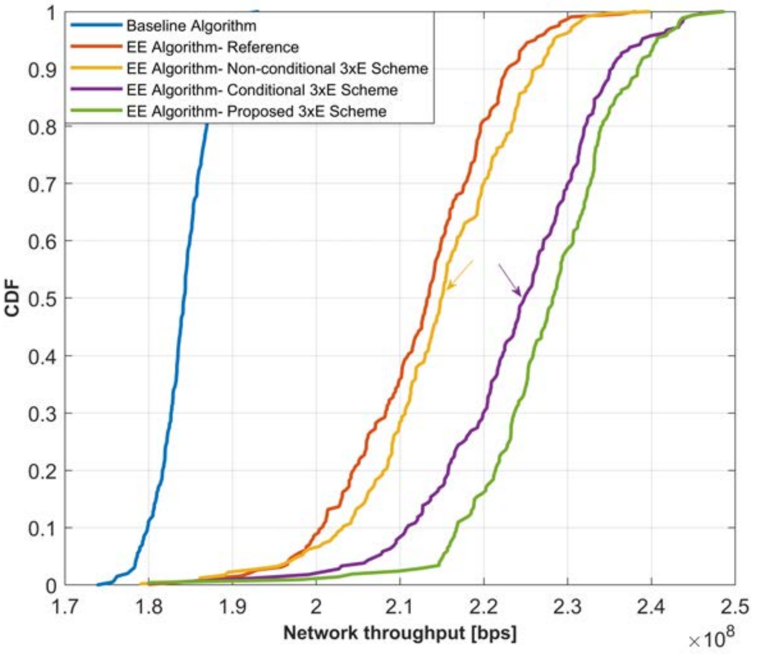


Figure 6.7: Network throughput with 150 RUs and 150 UEs.

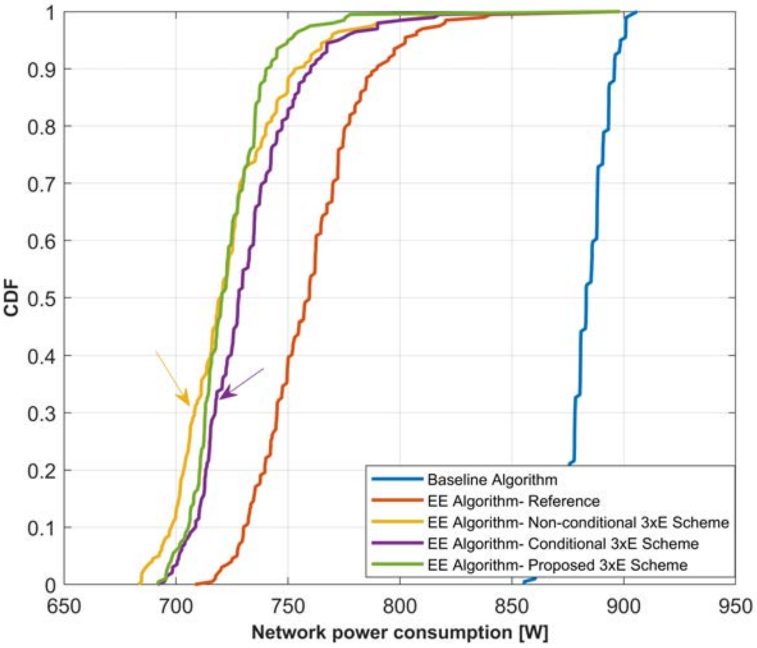


Figure 6.8: Network power consumption with 150 RUs and 150 UEs.

ments. Therefore, the rest of the analysis has been done for the hexagonal deployment to consider a uniform deployment within the cell-less RAN architecture, aligned with a cellular network topology. The figures (Fig. 6.5 and Fig. 6.6) show the benefit of conditional interference management in interfering scenarios with lower population of UEs. In such scenarios, low loaded RUs with high λ_m(interference contribution ratio) will be prevented from being active through a certain loop. However, highly loaded RUs with high λ_m that are not energy efficient will also be made to sleep through the conditional loop. In this case, due to the lower user densification, a lower number of RUs with low load will have high λ_m in order to enter the certain loop. Therefore, the conditional loop will make the remaining higher loaded RUs sleep depending on their impact on the network and minimum individual EE performance. Fig. 6.7 shows that the conditional and proposed ($3\times E$) schemes provide a higher amount of transmitted bits and network throughput compared to the reference algorithm and the non-conditional scheme. As it is shown in Fig. 6.8, the non-conditional scheme has lower power consumption due to placing more RUs in sleep mode as compared to the conditional scheme. However, some of the slept RUs may have been efficient in terms of transmitted bits per energy unit. Therefore, reconsidering RUs from the $M_{\text{G-active}}$ set for sleep mode through a conditional scheme will assure an EE gain as compared to the non-conditional scheme in low loaded scenarios, as shown in Fig. 6.6.

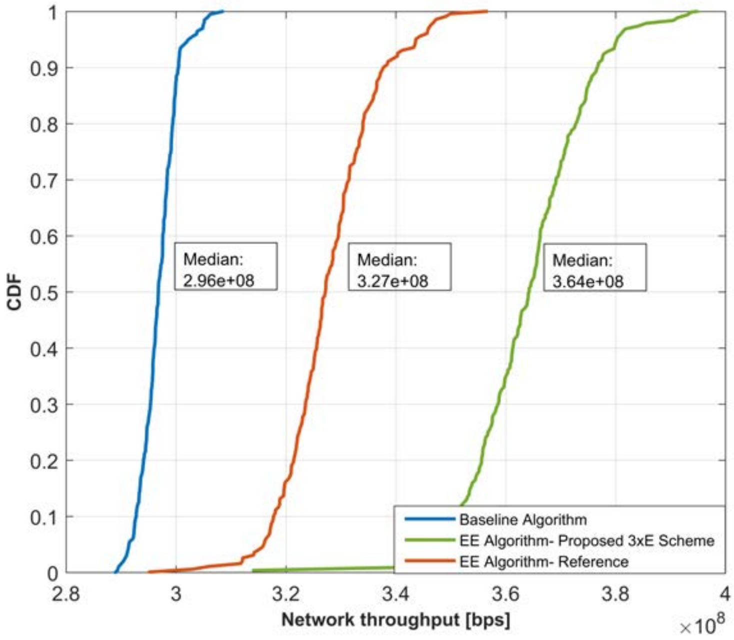


Figure 6.9: Network throughput with 150 RUs and 250 UEs.

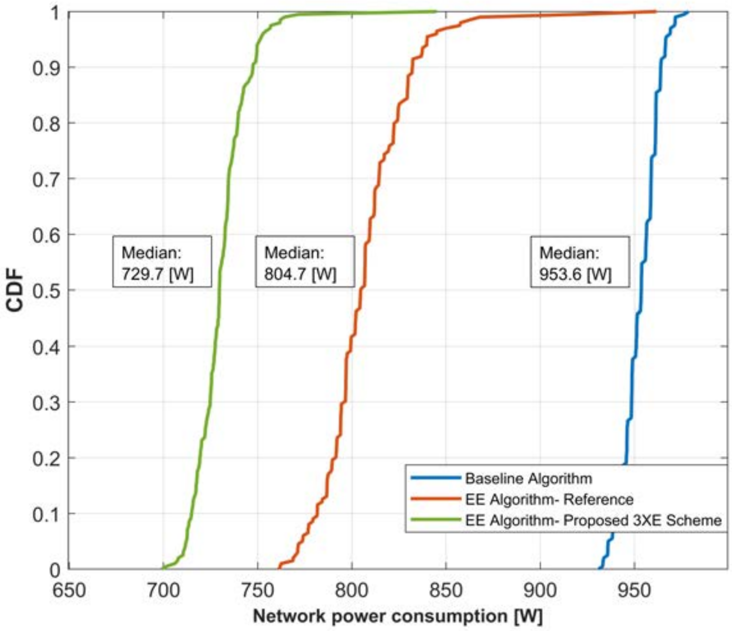


Figure 6.10: Network power consumption with 150 RUs and 250 UEs.

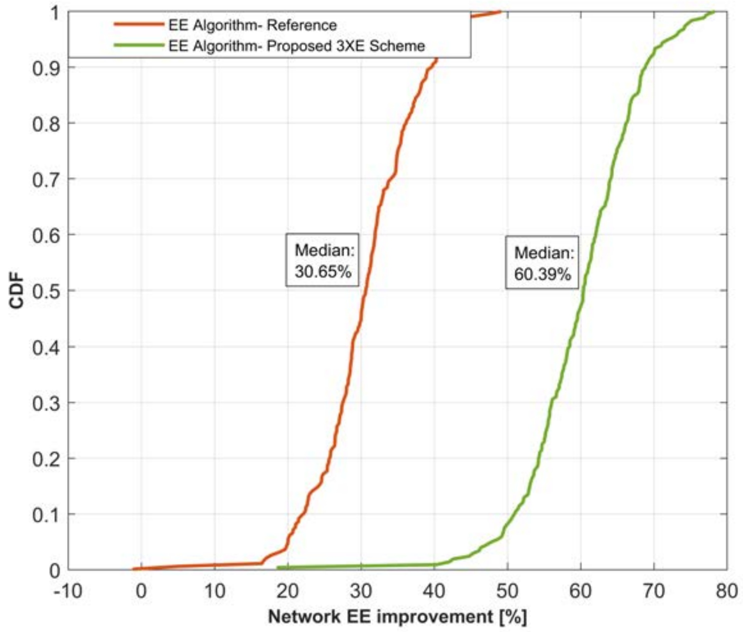


Figure 6.11: Network EE improvement over baseline with 150 RUs and 250 UEs.

The remaining simulations are performed for 150 RUs and 250 UEs to analyze more general scenarios reflecting dense networks. Fig. 6.9 presents the simulation results for network throughput. The proposed ($3 \times E$) algorithm outperforms [92] and the baseline algorithm within the dense cell-less network. The interference management considerations within proposed loops and traffic loss control support the network throughput enhancement, compared with the conventional scheme. The total power consumed by all the RUs is shown in Fig. 6.10. Considering the applied proposed certain sleep loop to make inefficient RUs sleep, in addition to strict control over the RUs in terms of energy efficiency which do not violate all the criteria, will not let any power wasting RU stay active through the conditional loop. This is the reason why the proposed scheme shows the lowest consumed power compared with the other three algorithms. The CDF of the network EE improvement is shown in Fig. 6.11. It is observed that the expected performance enhancement was satisfied thanks to the network throughput improvement and saving the power consumption through certain and condition sleeping RU loops. There is an improvement over the baseline algorithm in the order of 60%, almost doubling the EE enhancement with respect to existing competing alternatives.

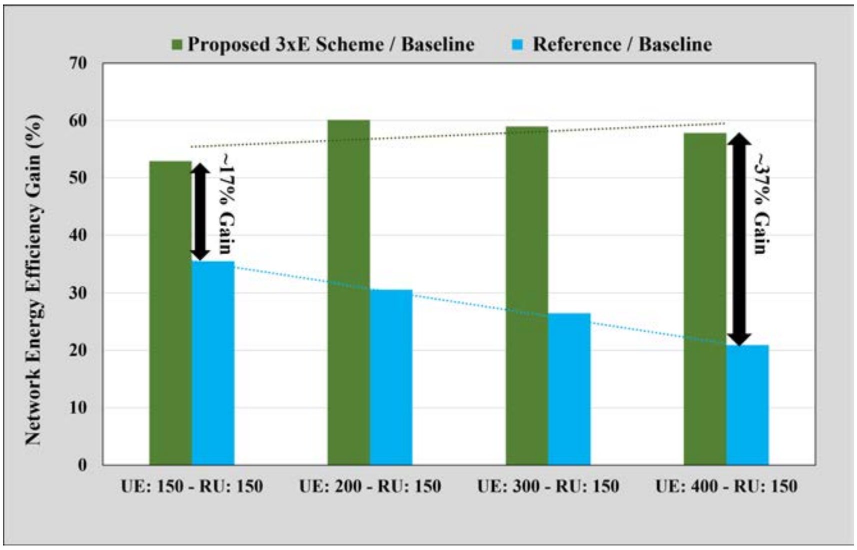


Figure 6.12: Network EE sensitivity to UE densification with 150 RUs.

To analyze the sensitivity of our proposed scheme to UE densification, we have simulated the schemes with an increased number of UEs and a fixed number of 150 RUs. The obtained network EE gain of the proposed ($3 \times E$) RU sleep mode selection and the reference algorithm over the baseline algorithm are plotted in Fig. 6.12. The UE densification increment will increase the load of the RUs and reduce the interference ratio per RU. The

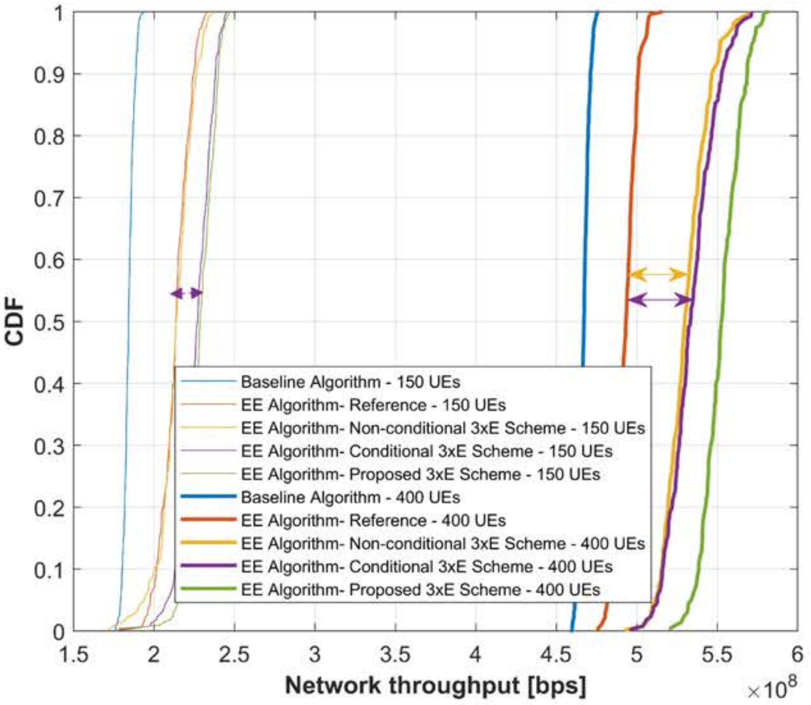


Figure 6.13: Network throughput sensitivity to UE densification with 150 RUs.

number of RUs meeting the criterion to enter the sleep mode will be decreased due to the high load in the RUs. Hence, the energy saving will be smaller. Therefore, the reference algorithm will have a significant EE performance degradation in user-densified scenarios because of its main criteria based on the RUs load. On the other hand, having a lower interference contribution ratio will cause lower interference in the network and, therefore, higher throughput will be achieved. In high user-densification scales, our proposed scheme will gain in EE performance thanks to the certain loop criteria based on the interference contribution of low loaded RUs. This is in addition to making highly loaded and non-energy efficient RUs sleep through a conditional loop. Therefore, the proposed $(3{\times}E)$ scheme has a higher performance gain with respect to the reference algorithm, more than 35% within the more populated area. It shows that our proposed scheme manages interference in the network even in the densely populated scenarios, while the conditional sleeping RU loop will take care of the performance dependency on the densification intensity. Thus, it avoids the performance degradation in low-loaded environments. The stability of the performance of the proposed $(3 \times E)$ to the user densification as compared to the reference scheme is shown in Fig. 6.12.

Fig. 6.13 shows how the conditional loop avoids a throughput degradation in a low-load network as compared to the non-conditional ($3 \times E$) scheme. In contrast, in a highly densified scale, such as 400 UEs in our simulation setup, the conditional loop does not add any advantage, while the performance is maintained. Thanks to these facts, the network will keep running in an energy-efficient way for different scales in a very stable manner. These attributes prove the stability of our proposed approach regarding EE.

6.4 Concluding Remarks

In this chapter, an energy efficient sleep mode scheme ($3 \times E$) was proposed that carefully selects and makes inefficient RUs sleep to enhance the EE of a cell-less RAN architecture in 5G and beyond 5G networks. The proposed scheme approaches EE optimization by increasing the transmission rate per energy unit by means of energy saving (instead of a mere power consumption minimization approach). To ensure a stable performance enhancement in networks with a higher user density, as well as in scenarios with lower density of users, the interference contribution of each RU is considered within the proposed criteria. The ($3 \times E$) scheme manages the interference through the two-step sleeping loop in a way that not only enhances the network EE, but it also ensures that the minimum EE of active RUs is not being degraded as an additional constraint. Considering the network EE as the main objective function, we made a conditional sleeping loop for RUs to guarantee the EE enhancement. The conditional interference mitigation in our proposal would control the lower populated networks' EE even if the distributed load within RUs is temporarily meeting the configuration thresholds. Simulation results showed that the proposed scheme provided a significant advantage (up to 60%) over several competing alternatives not only in low-load scenarios, but also in highly-loaded ones. It is worth to note that our proposal adds a performance improvement as compared to the reference algorithms in scenarios with higher density of users. In contrast to previous works that did not address the performance stability of sleep mode schemes in peak-traffic hours, ($3 \times E$) scheme provides a stable enhancement against various loads and interference due to the increment of the number of UEs in the network within the same topology. The current findings add substantially to our understanding of network EE regardless of user density variations and the load of 5G and beyond 5G networks. Next chapter will explore the multi-architecture coexistence network scenarios, i.e., cell-less and cellular.

Chapter 7

Multi architecture coexistence network

The recently coined concept of cell-Less RAN architecture clearly matches the beyond 5G expectation of achieving more spectral efficiency. However, the roll out of any novel solution like cell-less within the entire network is time consuming and challenging. Therefore, there is a need to enable the coexistence of newly deploying architectures with existing networks. In this chapter a multi-architecture coexistence (MACO) network model is proposed to enable inter-connection of different architecture through coexistence and cooperation logical switches in order to enable smooth the deployment of cell-less architecture within the legacy network. In addition to its impact on performance enhancement, more usage of existing architecture to contribute to the partially deployed cell-less network will provide the higher cost-efficiency in terms of network migration toward the ideal entire cell-less RAN as well as smooth compatibility alignment of architectures. Simulation results show that the proposed model for coexistence of cell-less and cellular architectures will provide a higher network quality of experience for the users compared to legacy cellular networks. The proposed MACO network will ensure better network performance for a massive number of users which is a challenging concern beyond 5G networks. The content of this research is published as a research article [13] in IEEE Conference on Standards for Communications and Networking (CSCN 2022), Greece.

The rest of the chapter is organized as: Section 7.1 presents the system model with cooperative and competitive scheduling; Section 7.2 discusses the proposed MACO model; Section 7.3 depicts the simulation results; and Section 7.4 draws the conclusion of the work presented in this chapter.

7.1 System Model

In the proposed MACO model shown in Fig. 7.1, the network can be implemented in conjunction with an Open RAN or other standard that is based on interoperability and standardization of RAN elements. This includes a plurality of RUs such as RRHs or other radios, each with one or more antennas that are supported by processing, such as a combination of DUs and CUs. The RAN controller (RANC) can be a central smart controller, RAN intelligent controller or other central controller, that operates by managing the UE/RUs connections, the RUs dynamic association to users and/or RU clustering in a cell-less architecture. With such dynamic adjustments, the cooperative scheduling implemented under control of the RANC can overcome the interference. Through the central controller, the resources are cooperatively scheduled, regarding association and clustering of RU, bandwidth and power. In the following section, we describe different scheduling approaches.

7.1.1 Cooperative Cell-Less Scheduling vs Competitive Cellular Scheduling

In the cell-less architecture, the resources available at different RUs, can be considered as a common pool of radio resources. This can increase the freedom of users in accessing bandwidth and allow for wider resource coordination within the system. For the scheduling to take the interference into consideration, the RANC is informed about the entire set of RUs managed under a given RANC status and coordinates the nodes in a cooperative schedule. In this way, the interference can be managed and taken only as a useful signal. As used herein, the terms competitive and cooperative scheduling can be summarized as follows:

- **Cooperative Scheduling:** resources of each RU consider status of the same resources from all RUs under the RANC management acting in an arbitrary mode of operation (centralized or distributed scheduling based on the functional splits).
- **Competitive Scheduling:** each RU's resources are allocated separately without considering other RUs scheduling status. So, there is no coordinating action from RANC.

Considering instead a cell-less architecture, the user is associated with the common resource pool and can be assigned resources dynamically without consideration of the user viewpoint, to which RU that resource is related to. Therefore, in an extreme case, RUs may be reassigned per TTI for each UE. Applying a cell-less RAN removes the cell boundaries in cooperative RRM mode of RANC based on a common resource pool. Such efficient scheduling can compensate for and/or benefit from the inter-cell CCI.

7.1.2 Cooperative Scheduling Supervision by RANC

Regarding cooperative scheduling, the RUs can be coordinated for resource pooling. The MAC layer schedulers can dynamically assign resources to the user from this common pool. To achieve better performance, the joint resource allocation and RU association can be performed within the cell-less architecture. The goal of the cell-less RAN scheduler is, through use of cooperative algorithms for example, to assign the best resources to the UE considering target KPI optimization (based on e.g., QoS parameters or other predefined system metrics). The cooperative scheduler can reallocate the resources to UEs to compensate for changes in the radio network conditions. Not only the RBs can be scheduled, but also the RU itself is considered an allocated resource, regarding the UE/RU association/allocation. In this cooperative cell-less dynamic scheduling, the CCI which is harmful to the UEs typically served at the same RB at the same time, is now treated as a useful signal via controlling the power and resource allocation from a centralized location. A joint optimization algorithm can be used to schedule/allocate these resources (RB, power, RU) for each UE.

7.2 Proposed Multi-Architecture Coexistence (MACO) Model

Fig. 7.1 illustrates the proposed model of a MACO network scenario with the cooperative cell-less scheduler and competitive cellular scheduler. From the network deployment planning point of view, all types of networks are evolving in time, including network swaps and roll out extensions. Architecture migration can benefit from intelligent planning to avoid the re-planning of network requirements from scratch and bring sustainability. Based on an available complex wireless network (e.g. composed of any homogeneous

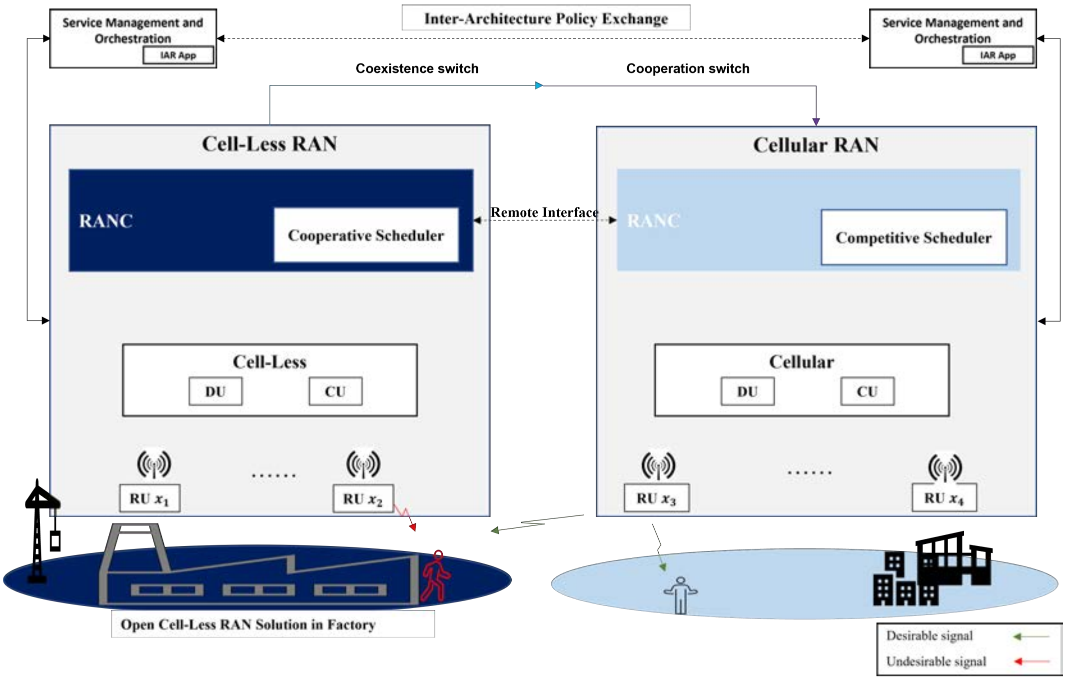


Figure 7.1: Proposed Multi-Architecture Coexistence (MACO) model with cell-less/cellular integration.

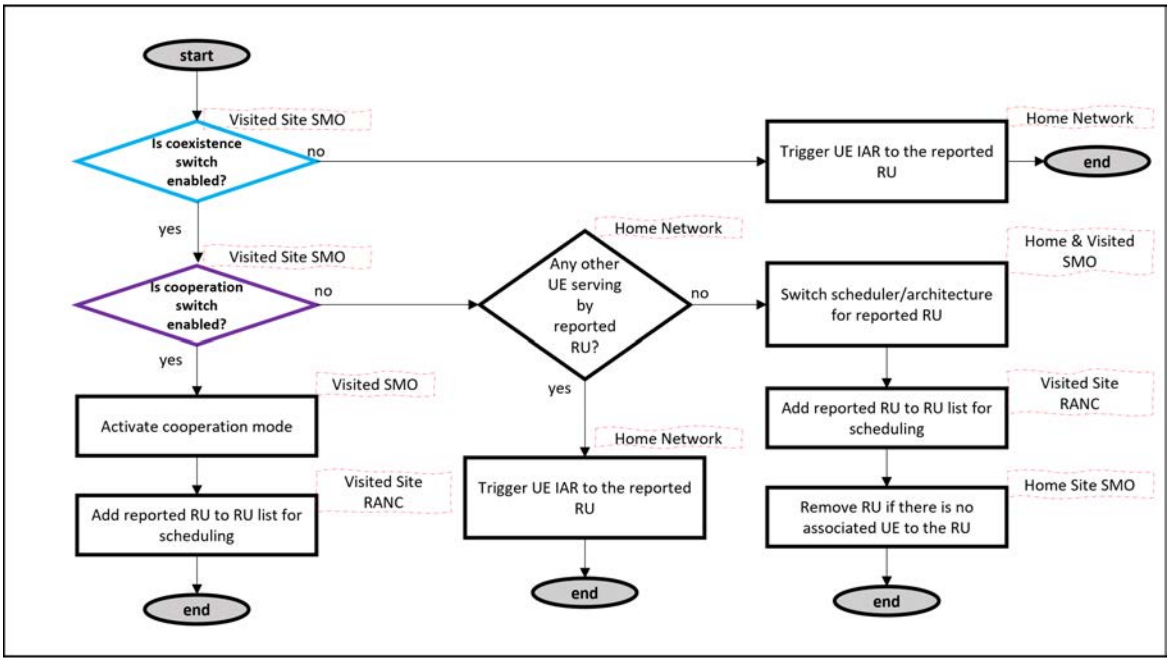


Figure 7.2: Flow diagram of the MACO model switch mode.

or heterogeneous network architecture), a self-configurable already deployed architecture facilitates adaptation to new architectures and network adjustments while reducing additional costs associated with re-planning. In addition, an existing architecture should be open to the potential of MACO while simultaneously facilitating the roll out of the different architectures according to the pre-defined awareness policies.

The coexistence architecture may support either a single operator or multiple different operators sharing the same infrastructure. In this regard, existing architecture supervision by the RANC creates the opportunity to support the coexistence of any combination of network partitions between network operators, for example, by adopting an inter architecture roaming (IAR) design and bringing it to the architecture's coexistence aspect. The MACO design using the RANC supports smooth and open network growth and architecture migration in addition to the ability to self-configure the network.

In order to apply the coordination and cooperation approach for resource allocation which addresses multiple RUs, a central smart controller is required. The RANC framework (which may follow open RAN specifications) brings the proper environment to allow coordinated approach for RU resources use and dynamically assign the resources to the users based on the user and network status. Part of the information of RUs will be exchanged via X2 interface, while the MAC layer schedulers of RUs will get the awareness information from RANC. Through this scheduling policy and status-aware handshaking of the RUs, the proper cooperation can be managed by RANC.

The cell-less RAN using the cooperative scheduling will bring a RU pool access. Although the user can use the whole available system resources, the specific part may be assigned to the user and will be reallocated dynamically based on the updated channel condition, user status, and the network situation. This will create the advantage of improving system performance by considering user performance within the system boundaries. The schedulers will be applicable real-time or near real-time depending on the implementation in RANC architecture. Each scheduler will be taken to coordinate with entire system schedulers by sharing their resource scheduling results, thanks to support of the centralized RANC.

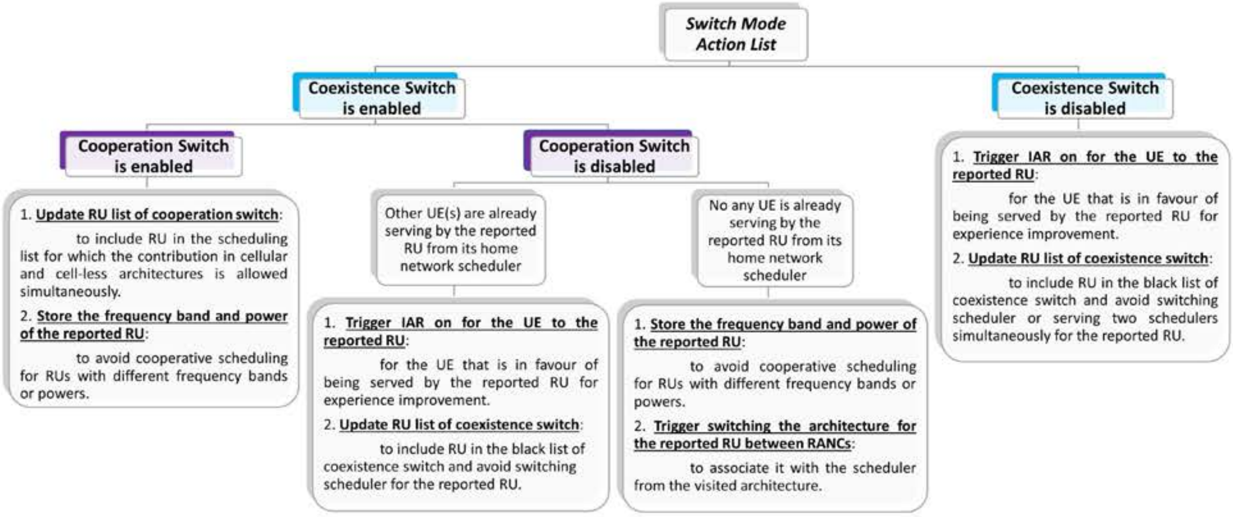
7.2.1 Cell-less and Cellular deployment in MACO model

Among the various new architectures available to network operators, cell-less RAN is one of the most advanced architectural evolution options to converge with existing RANs of the mobile network operators (MNO). The implementation of a cell-less RAN architecture may however face challenges where it should coexist and interconnect with legacy cellular network platforms and partitions. For example, in a mobile network operator's early deployment, users may be served by a cell-less network partition inside an office (indoor network partition like factory) due to improved capacity and limited spatial area of operation, provided by such a configuration. In this way, the coverage (i.e., indoor and outdoor) is served by the same MNO but there are two distinct architectures that coexist, i.e. cell-less and cellular. In this case, a UE leaving the cell-less indoor network and going outside to be served by external macro-cells (served according to legacy cellular-partition) needs a way to perform signaling similar to roaming with cooperation between the cellular AP and the cell-less scheduler to support handover (or tracking area functions). This can allow smooth transition between these two network architectures.

Another reason to switch a UE from a cell-less to cellular network segment may also be a "soft" transition such as: (a) the need to offload the UE in case the cell-less-partition is heavily loaded (e.g. conference, hot-spot area or busy-hour); and/or (b) the need to control access to a "restricted part" of the network – e.g. there is a meeting of supervisory board of the company that utilizes virtual, augmented or combined reality experience (VR/AR/XR) application that demands large bandwidth, minimal delays and limited access. The latter could be considered as a "traffic steering" use-case within a scheduling or security policy.

In general, the transmission mode may be triggered in few steps:

- UE measures the RF condition.
- Based on the measurement the handover request will be triggered.
- The Coexistence and Cooperation switch will be checked.
- The decision will be made, scheduler will be updated and the execution will be performed based on the decision.



1. **Update RU list of cooperation switch**: to include RU in the scheduling list for which the contribution in cellular and cell-less architectures is allowed simultaneously.
2. **Store the frequency band and power of the reported RU**: to avoid cooperative scheduling for RUs with different frequency bands or powers.

1. **Trigger IAR on for the UE to the reported RU**: for the UE that is in favour of being served by the reported RU for experience improvement.
2. **Update RU list of coexistence switch**: to include RU in the black list of coexistence switch and avoid switching scheduler for the reported RU.

1. **Store the frequency band and power of the reported RU**: to avoid cooperative scheduling for RUs with different frequency bands or powers.
2. **Trigger switching the architecture for the reported RU between RANCs**: to associate it with the scheduler from the visited architecture.

1. **Trigger IAR on for the UE to the reported RU**: for the UE that is in favour of being served by the reported RU for experience improvement.
2. **Update RU list of coexistence switch**: to include RU in the black list of coexistence switch and avoid switching scheduler or serving two schedulers simultaneously for the reported RU.

Figure 7.3: Action list for the proposed MACO model including coexistence and cooperation switches.

A pre-defined mechanism is required to develop the transmission mode (Cooperative Cell-Less or Competitive Cellular) and switch from one to another in the coexisting architecture. It could be triggered based on the traffic load and specific target KPIs such as network throughput, security or other criteria. However, preferences on cell-less or cellular configurations will be considered as triggering constraints.

The **coexistence/cooperation switch** is proposed to enable implementation of the cell-less RAN architecture interconnecting with the cellular network. As it is shown in Fig. 7.1, switch mode policy will be applied through the service level agreement (SLA) in the IAR application placed in the service management and orchestration layer. The possible place of each flow is indicated by a flag with a red outline. In Fig. 7.1, RU x_3 could possibly be the reported RU for potential UE (user with red outline), where cell-less network is considered as the visited side and cellular network is considered as home side for the reported RU (RU x_3). The example of the MACO switch mode flow diagram is shown in Fig. 7.2. However, depending on the status of RUs, the network will schedule radio resources differently considering the pre-defined action list extracted from the SLA. An example of the switch mode action list is shown in Fig. 7.3.

7.3 Performance Evaluation and Result Analysis

In our simulation setup, we assume a hexagonal network topology including 6 RUs with 500 m inter site distance (ISD), with 20 MHz bandwidth over a carrier frequency of 4 GHz. RU height is 25 m and UE height is 1.5 m. The maximum transmit power for any RU *m* is set as 44 dBm. The maximum UE throughput is considered as 1 Mbps for users to rationally compare performance of the serving architecture. The UEs are randomly deployed over the entire network and distributed among RUs. A simplified version of the channel model for Urban Macro test environment is implemented based on the defined model in [126], and associated path-loss models used in simulations are from [119]. In this section, we evaluate the following networks and compare their performance:

- **Cooperative Scheduler (Cell-less):** This performs cooperative scheduler within ideal cell-less RAN.
- **Competitive Scheduler (Cellular):** This performs a competitive scheduler within legacy cellular RAN.
- **Coexistence (Cell-less/Cellular):** This performs coexistence of competitive and cooperative schedulers within cell-less and legacy cellular RAN, respectively. It is assumed the coexistence switch is enabled and cooperation switch is disabled.

Fig. 7.4 plots the CDF of SINR of the scheduled UEs in the network for the scenario where the number of users is 600. It shows the advantage of coexistence networks in providing higher SINR closer to the ideal cell-less network compared to cellular networks. It is worth noting that the associated RAN scheduler in each network schedules radio resources (RU, RB) for all the UEs in cellular and cell-less networks and half of the UEs per architecture in coexistence networks, respectively. However, as it was shown in Fig. 7.5, the result of SINR enhancement is dominant when the number of UEs increases. This is because of more competition over RB allocations where the number of UEs is large. Hence, because of coexistence of cell-less and cellular architectures, the required number of serving RUs from cellular architecture could switch to the cell-less scheduler and improve network performance compared to the cellular. However, the best performance belongs to the cell-less network where all the UEs are scheduled by cooperative scheduler

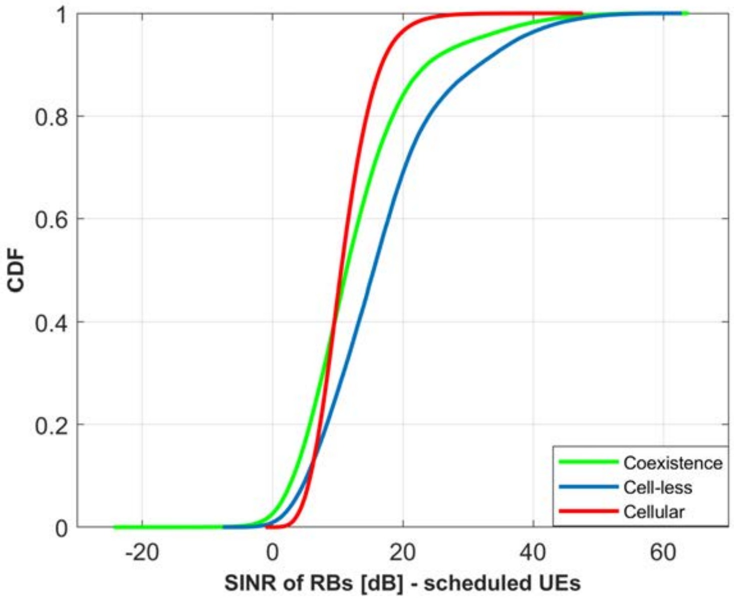


Figure 7.4: CDF of UEs SINR over allocated RBs for 600 Users.

within cell-less architecture. The entire network migration toward the cell-less architecture will be time consuming with high complexity as we described in previous sections. Therefore, it is worth it to start rolling out with coexistence of multi-architectures, where the resources could possibly switch between. Hence, as it is shown in the simulation results, UEs will have the opportunity to experience better performance from the network.

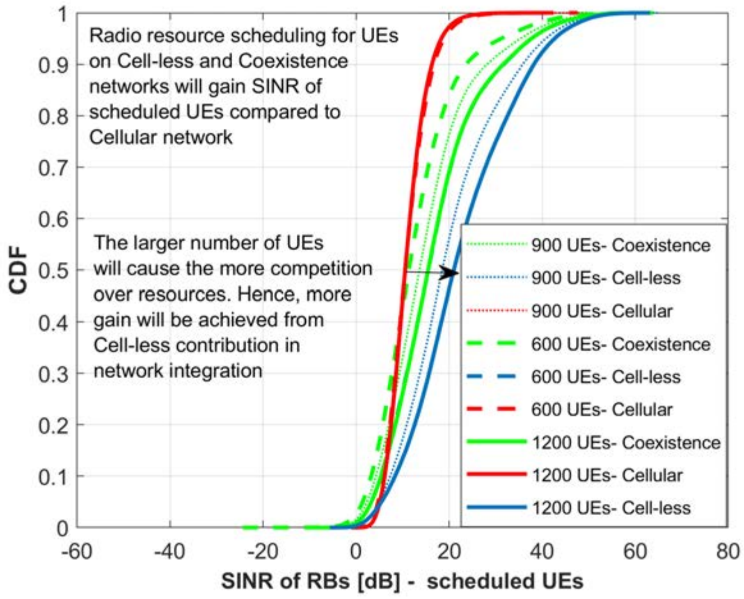


Figure 7.5: CDF of UEs SINR over allocated RBs for 600, 900, and 1200 Users.

7.4 Concluding Remarks

Novel solutions like Cell-less architecture have been considered as a technology enabler for beyond 5G networks. However, migration of the legacy network to a new architecture is time consuming. In addition to this, there are significant deployment complexities for the network-wide roll out. Cell-less architecture is a promising candidate among the solutions providing significant performance improvement for the beyond 5G networks by removing cell boundaries. Integration of cell-less network or any other competitive technology enabler with the existing legacy architecture is a critical need to enable a smooth path for network migration. Hence, in this chapter, the MACO network model was proposed for enabling cell-less architecture coexistence with legacy architecture along with network migration toward the ideal architecture where the network is cell-less entirely. Therefore, thanks to coexistence and cooperation modes, the proposed model will not only speed up the roll out and industrialization, but also will provide better performance behavior in the network as shown in the simulation results.

Chapter 8

Conclusion and Future Works

This thesis presents innovative solutions of RRM of the cell-less RAN architecture for future generation wireless networks. Moreover, an energy efficient solution is developed for this architecture. The focus of this thesis was mainly on issues as follows: (i) investigate suitable switching mode mechanisms in a multi-architecture coexistence network (cellular and cell-less); (ii) design of the cell-less architecture in the Open RAN framework; (iii) develop RRM solutions for cell-less RAN aiming to enhance throughput and URLLC performance; (iv) design energy efficient solutions for cell-less RAN architecture for future generation wireless networks. These issues were investigated, and suitable solution approaches were proposed. This concluding chapter summarizes the main findings and the contributions of this thesis. In addition, several research directions for future works are suggested.

8.1 Summary of the thesis

The main contributions of this thesis are summarized as follows:

- Chapter 3 details the design procedure of a cell-less architecture in the Open RAN framework in order to improve the network performance by enabling virtualization, centralization, and cooperative communication which could not only open the network, but also open the way toward efficient optimization functionalities. The strategy for the cell-less topology in Open RAN-based architecture is proposed to enable the network formation. In addition, the signaling flow adopted to the Open RAN is designed to establish the cell-less RAN. Thanks to this principle, the newly evolved Open cell-less RAN will support the entire interoperability among different vendors in a vertically converged RAN within tiers of smart cities and horizontally converged RAN among BSs in an open ecosystem.

- Chapter 4 proposes an efficient RRM algorithm for the cell-less RAN to improve the system capacity performance through aggregating the network level realization. The mathematical model, algorithm, and performance results from the associated simulations are also outlined. In this work, the approach of cell-less RAN is validated by considering the assumption of mitigating network level interference introduced by the utilization of the same resources of the underlying RUs. The potential benefits of the proposed approach and its RRM strategies over the legacy cellular RAN approach are highlighted through simulation results. In addition, the effect of user density on the proposed algorithm compared with the legacy networks are analyzed in terms of system capacity performance enhancement for a different scale of network setup in several deployment environments. The simulation results illustrate that the proposed cell-less NG-RAN design provides significant system capacity improvement over the legacy cellular solutions.

- Chapter 5 investigates an enhanced RRM scheme to minimize the latency of URLLC devices in a coexistence network scenario with eMBB for a cell-less RAN architecture. This scheme improves the latency performance by an efficient scheduling that considers the number of resources required for delivery of URLLC packets. In this work, a TD scheduler is developed by proposing a ranking algorithm from a RU perspective which will support the efficiency of scheduling in terms of resource consumption in large scale networks. Also, a FD scheduling algorithm is introduced by using the ICR-based approaches to avoid the eMBB users throughput degradation that can be caused by competition of newly admitted users to the network with existing ones. The proposed scheme has a 29% latency improvement for URLLC and 90% SINR improvement for eMBB users as compared with conventional scheduling policies.

- Chapter 6 develops an energy-efficient scheme in the cell-less architecture towards its practical deployment in 5G and beyond networks. This includes a two-step sleep mode selection (i.e., certain phase and conditional phase) with an intelligent controller that dynamically updates the user and RU association and switches the unnecessary RUs to sleep. The proposed approach controls the interference at dense environments in a way that transmission is performed only if it is beneficial for the increment of the network EE. Meanwhile, the proposed $(3 \times E)$ scheme employs conditional sleeping criteria with traffic load-based customization in addition to an interference consideration to assure maintaining efficient power saving for networks with various user densities. Simulation results show that the network EE is improved up to 30% compared to the reference algorithm and up to 60% with respect to the baseline algorithm in which all APs are active all the time.

- Chapter 7 proposes a multi-architecture coexistence (MACO) model to enable interconnection of two different architectures, i.e., cellular and cell-less. This will allow the legacy architecture transition to the cell-less architecture, where they perform cooperative communication toward beyond 5G network. Moreover, the switching modes i.e., coexistence switch and cooperation switch in the MACO models are presented which could be used for real-time and near real-time applications.

8.2 Future Works

This section suggests some possible extensions to the works presented in this thesis.

8.2.1 Investigate the performance of multi-tenant cell-less RAN architecture

In this thesis, the behavior of the proposed cell-less RAN design is investigated to maximize the network performance. There is very little research tracking in the KPIs of multi-tenant infrastructure of this type of network design within Open RAN architecture. Therefore, future research planned by the candidate will explore the performance optimization opportunities.

8.2.2 Exploring the impact of transmission time and dynamic slicing

Considering the latency for URLLC users and network throughput for eMBB users as the main objective functions, we make customized TD and FD schedulers within our proposed RRM scheme. However, the impact of transmission time and dynamic slicing are not considered for this work. Therefore, future research will consider the impact of transmission time and additional dynamic slicing algorithms for optimum coexistence of URLLC and eMBB users, enhancing the cell-less network performance as a strong enabling technology for beyond 5G networks.

8.2.3 Investigate the signaling flow for coexistence network

In the network migration to beyond 5G, it is important to switch on the MACO toward open end-to-end communication. However, further works planned by the candidate will investigate the detailed signaling flow of the proposed MACO model.

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