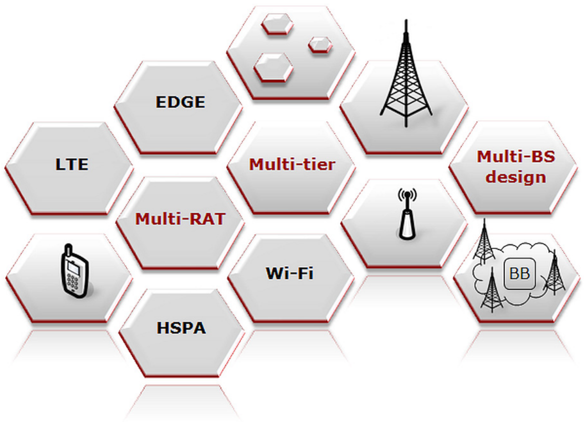


4G and Beyond - Exploiting Heterogeneity in Mobile Networks

Anna Zakrzewska
Ph. D. Thesis
December 2013

DTU Fotonik
Department of Photonics Engineering

4G and Beyond
- Exploiting Heterogeneity in Mobile Networks

Anna Zakrzewska

December 2013

Networks Technologies and Service Platforms
DTU Fotonik
Technical University of Denmark
Ørsteds Plads 343
2800 Kgs. Lyngby
Denmark

T.T.T.

Jeg har skrevet et sted,
hvor jeg daglig må se,
det manende tankesprog:
T.T.T.

Når man føler hvor lidet
man når med sin flid,
er det nyttigt at mindes, at
Ting Tar Tid.

Put up in a place
where it's easy to see
the cryptic admonishment:
T.T.T.

When you feel how depressingly
slowly you climb,
it's well to remember that
Things Take Time.

Piet Hein

Preface

This thesis presents a selection of the research work conducted during my Ph.D. study from June 15^{th}, 2010 until December 6^{th}, 2013.

The project was mainly done in the Networks Technology and Service Platforms group, at the Department of Photonics Engineering, Technical University of Denmark under supervision of Associate Professors Michael S. Berger and Sarah Ruepp.

A 6 months research stay took place at Bell Laboratories, Alcatel-Lucent in Dublin, Ireland, under supervision of Dr. David López-Pérez and Dr. Holger Claussen.

This Ph.D. study, the external research stay and participation in international conferences was financed by the Technical University of Denmark, The Danish Advanced Technology Foundation through project SAIRS "Standard Agnostic Intelligent Radio Systems for the High Capacity Wireless Internet", as well as travel grants from Otto Mønsteds Fond, Oticon Fond, P. A. Fiskers Fond and ACM N^2 Women.

Abstract

Current and future mobile networks will constitute of multiple coexisting Radio Access Technologies (RATs), cells of different size (macro-, metro-, pico-, femtocells) forming a Heterogeneous Network (HetNet), and Base Stations (BSs) of various architectures. This thesis addresses different aspects of mobile networks and focuses on the main challenges resulting from their heterogeneity.

To effectively manage this diversity, a novel hierarchical approach considering all types of resources, spectral, optical and computational is proposed. The generic framework covers all kinds of network heterogeneity and can be beneficial at any stage of network deployment or operation. Furthermore, a dedicated study of RAT selection and resource allocation is performed and a new optimisation model is introduced and evaluated. The results show a significant reduction of number of handovers at the cost of a slight throughput degradation, which leads to a more stable connectivity in multi-RAT environments.

A new HetNet architecture with control and user plane separation is thoroughly evaluated. The study focuses on the soft-pilot requirements and assignment problem, which is solved using a proposed optimisation model and a number of heuristic approaches. The analysis for a number of deployment scenarios demonstrates the feasibility of this architecture. Furthermore, the obtained results show the potential benefits of the new architecture in terms of mobility management and energy efficiency.

Network sharing has become a common strategy among network operators and it is important to evaluate the benefits of such cooperation. A teletraffic theory analysis for various network dimensioning approaches is provided and based on the results clear recommendations are given.

All the presented concepts are standard agnostic, meaning that they can be applied to any RAT, including technologies that have the potential to become part of the next generation mobile networking. This makes the proposed solutions universal and in line with the current trends to design future mobile networks.

Resumé

Nuværende og fremtidige mobilnet vil bestå af multiple, sameksisterende Radio Access Teknologiers (RAT), forskellige cellestørrelser (makro-, metro-, pico- og femtoceller) udgørende et heterogent net (HetNet), samt forskellige basestationsarkitekturer. Denne afhandling behandler forskellige aspekter af mobilnet med fokus på de vigtigste udfordringer skabt af denne heterogenitet.

Til effektivt at styre denne diversitet, foreslås her en nyskabende hierarkisk metode, der tager alle ressourcer, spektrale, optiske og processorkraft, i betragtning. Dette generiske framework dækker alle former for netværksheterogenitet og kan være gavnlig i alle faser af netværksudrulning og drift. Ydermere er et dedikeret studie af RAT-selektion og ressourceallokering blevet udført og en ny optimeringsmodel introduceres og evalueres. Resultaterne viser en signifikant reduktion i antallet af handovers på bekostning af et mindre fald i throughput, hvilket fører til mere stabile forbindelser i multi-RAT miljøer.

En ny HetNet-arkitektur med adskilt control- og user-plane bliver undersøgt grundigt. Studier her fokuserer på problemet med krav til og tildeling af soft-pilot, og der foreslås en optimeringsmodel samt et antal heuristikker. En analyse af en række udrulningsscenarier demonstrerer anvendeligheden af denne arkitektur. Ydermere viser resultaterne de potentielle fordele ved denne arkitektur med hensyn til mobility management og energieffektivitet.

Netværksdeling er efterhånden blevet en udbredt strategi for operatører og det er vigtigt at få undersøgt fordelene ved sådan et samarbejde. Her foretages en teletrafikteoretisk analyse af forskellige tilgange til netværksdimensionering, hvilket udmunder i konkrete anbefalinger.

Alle de præsenterede koncepter er standard-uafhængige, hvilket vil sige, at de kan anvendes på enhver RAT inklusive teknologier, der har potentialet til at blive brugt i næste generations mobilnet. Dette gør de foreslåede løsninger universelle og i tråd med aktuelle tendenser i design af fremtidens mobilnet.

Acknowledgements

The adventurous journey of my Ph.D. study is about to end. Those who have met me, quickly recognize that I love travelling. The desire to travel, meet new people, visit new places and learn about other cultures is not much different from research. Both require curiosity and dedication, sometimes careful planning or more intuition and spontaneity. Hereby, I would like to acknowledge those who have helped me along the way.

I am very much grateful to my supervisors, Associate Professors Michael S. Berger and Sarah Ruepp for their guidance, encouragement and trust to let me explore and find my path. They provided all the necessary support so that I did not drown while diving in the ocean of wireless communication research.

With a great delight I thank Dr. Villy B. Iversen who took me for a trip to unknown regions of teletraffic theory. His knowledge and research spirit made it truly explorative.

I thank also Dr. Fabio D'Andregiovanni from Zuse Institut Berlin who showed me new better paths to climb the operations research mountain.

I am deeply indebted to Dr. David López-Pérez and Dr. Holger Claussen from Bell Laboratories, Alcatel-Lucent in Dublin who invited me and guided during my external research stay. I acknowledge their strong dedication, creativity and enthusiasm that are a great source of inspiration for me. This adventure was like a balloon flight, showing me the wireless landscape from an industrial perspective. I am thankful to all colleagues from Bell Labs for a very warm welcome and all the help.

This external stay would not have been possible without the involvement of Prof. Ejner Nicolaisen and everyone dealing with its formal aspects. I extend my appreciation to the administrative personnel of DTU Fotonik. Thank you very much for your help and assistance.

I am grateful to my collaborators, colleagues and office mates from the Networks group for fruitful teamwork, especially on the management framework, valuable advice and great atmosphere that made this journey much more joyful.

I acknowledge those, who helped fixing my 'Ph.D. bike'. Dr. Lars Staalhagen has been of a great help with all OPNET related questions. Aleksandra Chećko, Dr. Łukasz Brewka, Dr. Henrik Christiansen, Dr. David López-Pérez and my supervisors dedicated their time to review parts of this thesis- I highly appreciate all the comments and suggestions. Mange tak til Dr. Henrik Christiansen for translating the abstract.

I would like to thank Dr. Mirjam Godskesen, who gave me a valuable Ph.D. driving lesson- I made it through without crashing.

I thank my fellows from IEEE Student Branch DTU for side trips from the main Ph.D. track and all the events we organised together.

This thesis is a result of slightly more than three years of work but the journey started much earlier and I would like to take this opportunity to thank all those that had an influence on my personal development.

Dr. Leszek Koszałka and Prof. Ryszard Zieliński from Wrocław University of Technology, Poland once upon a time showed me a map of research and assisted when I was making the first steps. I greatly acknowledge their support to all my initiatives throughout the years.

I owe words of gratitude to Halina Łapińska and Wojciech Jaśkiewicz, who helped me go along some bumpy roads and showed that dreams come true through persistence.

I would also like to thank my friends from all over the world who always fill my suitcase with lots of smile and encouragement. Thanks to Ola and Artur for taking care of me in Dublin.

I am grateful to aunt Nora and uncle William for support, keeping their fingers crossed miles away and emergency English consulting.

It is my heart full of feelings to thank Grzegorz, who has been patiently waiting for my return to begin a new journey.

Finally, I express my enormous gratitude to my mom for her commitment and understanding. I would never reach this point if not her brave decision nearly 20 years ago. Dziękuję!

Kongens Lyngby, December 6th, 2013 Anna Zakrzewska

Ph.D. Publications

This Ph.D. project has resulted in 14 peer-reviewed publications [1-14] listed below in reverse chronological order.

[1] **A. Zakrzewska**, S. Ruepp, M. S. Berger, "Towards Converged 5G Mobile Networks- Challenges and Current Trends", accepted for publication by ITU-T Kaleidoscope, June 2014.

[2] **A. Zakrzewska**, D. López-Pérez, S. Kucera, H. Claussen, "Dual Connectivity in LTE HetNets with Split Control- and User-Plane," 9th Broadband Wireless Access Workshop, IEEE Globecom 2013,Atlanta, USA, Dec. 2013.

[3] **A. Zakrzewska**, S. Ruepp, M. S. Berger, "RAT Selection and Resource Allocation in Heterogeneous Networks -OPNET Modeler in Optimization Studies," OPNETWORK 2013, Washington D. C., USA, Aug. 2013. **Distinguished Technical Paper**

[4] E. Kisielius, A. Popovska Avramova, **A. Zakrzewska**, S. Ruepp, "SON Mechanisms for Energy Efficient LTE Networks," OPNETWORK 2013, Washington D. C., USA, Aug. 2013.

[5] A. Dogadaev, A. Checko, A. Popovska Avramova, **A. Zakrzewska**, Y. Yan, S. Ruepp, M. Berger, L. Dittmann, H. Christiansen, "Traffic Steering Framework for Mobile-Assisted Resource Management in Heterogeneous Networks", Ninth International Conference on Wireless and Mobile Communications, ICWMC, Nice, France, July 2013.

[6] **A. Zakrzewska**, A. Popovska Avramova, H. Christiansen, Y. Yan, A. Checko, A. Dogadaev, S. Ruepp, M. S. Berger, L. Dittmann, "A Framework for Joint Optical-Wireless Resource Management in Multi-RAT, Heterogeneous Mobile Networks", Workshop on Optical-Wireless Integrated Technology for Systems and Networks (OWITSN) 2013, IEEE ICC 2013, Budapest, Hungary, June 2013.

[7] **A. Zakrzewska**, F. D'Andreagiovanni, S. Ruepp, M. S. Berger, "Biobjective Optimization of Radio Access Technology Selection and Resource Allocation in Heterogeneous Wireless Networks", RAWNET/WNC3 2013, The 9th Inter. Workshop on Resource Allocation, Cooperation and Competition in Wireless Networks, WiOpt 2013, Tsukuba Science City, Japan, May 2013.

[8] **A. Zakrzewska**, S. Ruepp, M. S. Berger, "Cell Selection Using Recursive Bipartite Matching", INFOCOM Student Session, INFOCOM 2013, Turin, Italy, Apr. 2013.

[9] **A. Zakrzewska**, A. Popovska Avramova, S. Ruepp, M. S. Berger, L. Dittmann, "CSMA-based SON Mechanism for Greening Heterogeneous Networks", INFOCOM Student Session, INFOCOM 2013, Turin, Italy, Apr. 2013.

[10] **A. Zakrzewska**, V. B. Iversen, "Resource Sharing in Heterogeneous and Cloud Radio Access Networks", International Congress on Ultra Modern Telecommunications and Control Systems (ICUMT), pp 41-46, St. Petersburg, Russia, Oct. 2012.

[11] **A. Zakrzewska**, "Radio Resource Management in Heterogeneous Networks", Google Scholars' Retreat, Zurich, Switzerland, June 2012.

[12] **A. Zakrzewska**, M. S. Berger, S. Ruepp, "Modeling Multistandard Wireless Networks in OPNET", OPNETWORK 2011, Washington D. C., USA, Aug. 2011.

[13] **A. Zakrzewska**, M. S. Berger, S. Ruepp, "RRM Strategies for LTE and WiMax Interworking System", Second Nordic Workshop on System and Network Optimization for Wireless (SNOW), Salen, Sweden, Feb. 2011.

[14] **A. Zakrzewska**, M. S. Berger, S. Ruepp, "Multistandard Radio Systems: State of the Art and Research Issues", BONE- Celtic Tiger2 Workshop, Budapest, Hungary, Sep. 2010.

Contents

List of Figures

List of Tables

Chapter 1

Introduction

We observe significant changes within the field of wireless communication nowadays. It could be best described as an accelerating evolution of wireless networks driven by significantly growing user demands. With very fast proliferation of mobile devices and a plethora of new services, users require access any time, anywhere and with any kind of device. Therefore, providing a truly ubiquitous access through integration of various wireless standards with cells of different sizes, and building one consistent and compatible broadband system is a major goal of wireless communication. Equipment vendors, mobile operators, as well as standardisation bodies such as Institute of Electrical and Electronics Engineers (IEEE) and Third Generation Partnership Project (3GPP) focus their research efforts towards providing seamless service and meeting the rapidly growing end-user expectations. However, before such agnostic wireless systems independent from underlying technology come into life, a number of challenges related to network diversity in terms of standards, cell size and network architecture need to be overcome.

1.1 Background

Evolution of wireless systems has led to the development of heterogeneous networks, where heterogeneity can be defined in a number of dimensions. First, as a set of coexisting and cooperating Radio Access Technologies (RATs), such as Global System for Mobile communication (GSM), High Speed Packet Access (HSPA), Long Term Evolution (LTE), and Wireless Fidelity (WiFi). Secondly, a network can be comprised of cells of various sizes, e.g. macro-, metro-, pico- and femtocells that form multi-tier Heterogeneous Networks (HetNets)[1]. Another type of diversity comes from the main point of the Radio Access Network (RAN), which is the Base Station (BS) itself. It can be built in many different ways. For instance BSs can have closely connected or more separated Radio Frequency (RF) and Baseband (BB) processing units. Further on, from a hardware and software perspective, they can utilise products manufactured by different vendors and finally offer the end-users huge variety of services with diverse Quality of Service (QoS).

This thesis considers these three aspects of mobile heterogeneous networks. Following subsections will introduce them more in detail and discuss key features together with main research challenges and thesis contributions in each of the areas.

1.1.1 Multi-RAT Networks

The past thirty years have seen increasingly rapid advances in the field of mobile communication. Since the introduction of Nordic Mobile Telephony (NMT) in 1981 recognized also as First Generation (1G), mobile systems have undergone multiple upgrades driven by the increasing users and market requirements. The widely deployed Second Generation (2G) mobile networks introduced Short Message Service (SMS) and data enhancement in subsequent technologies, i.e., General Packet Radio Service (GPRS) and Enhanced GPRS (EDGE). The Third Generation (3G) family of mobile networks offers much higher data rates when compared with predecessors, and therefore enables services such as video streaming or podcasting, and makes data services more common. Finally, Long Term Evolution-Advanced (LTE-A) and IEEE 802.16m known as Wireless Interoperability for Microwave Access (WiMAX) 2.0 or Wireless MAN-Advanced are classified as Fourth Generation (4G) technologies, as they meet International Telecommunication Union-Radiocommunications Sector (ITU-R) requirements set towards International Mobile Telecommunications Advanced (IMT-Advanced) mobile systems (peak data rate of 100 Mbps and 1 Gbps for low and high mobility scenarios, respectively) [17].

[1]The term *heterogeneous network* covers all types of heterogeneity, whereas *HetNet* refers to a network with different cell sizes.

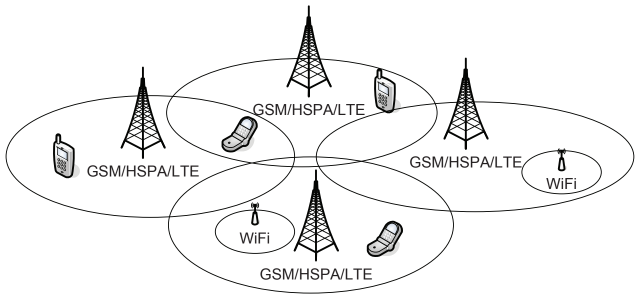


Figure 1.1: Multi-RAT network.

As a result of such evolution, today the wireless landscape is to a high extent shaped by a mixture of various RATs, as presented in Fig. 1.1. The work on multi-RAT systems started with the development of Universal Mobile Telecommunication System (UMTS) [18] and gained much attention with the appearance of WiMAX [19, 20]. The goal was to provide seamless interworking of different RATs within one multi-RAT system. Since 3GPP LTE Release 8 integration with both, 3GPP and non-3GPP technologies is also possible. While the other 3GPP networks, e.g., UMTS, are integrated directly via the Serving Gateway (S-GW), the non-3GPP access technologies can be connected to the S-GW via the Packet Data Network Gateway (P-GW) [21, 22].

Considerable research efforts have been dedicated to address the challenges of multi-RAT networks related to interworking, Radio Resource Management (RRM) and Always Best Connected (ABC) paradigm.

Interworking

Users and network operators could greatly benefit from a flexible multi-RAT platform. The first ones are able to choose the service based not only on the connection quality but also a set of other parameters including the service cost as well. On the network side, it increases the overall network capacity and allows for a better traffic load balancing among RATs. As a result, cooperation between RATs leads to better performance of the network as a whole when compared to individual ones. However, integrating different technologies is the major step that needs to be undertaken to achieve it.

In the literature, there are many different proposals of creating an interworking architecture between various RATs [20, 23–25]. A common approach is to define the cooperation levels that differ in terms of network architecture and supported interworking functions, starting from the simplest level of loose coupling, where both systems share only a common billing centre, to very tight coupling, that allows the users to handover between the RATs in a seamless way. Different levels presented in detail in [24] are summarized below.

a) Visited Network Service Access
In this mode, users are allowed to use the services offered by the other network. It requires Authentication, Authorisation and Accounting (AAA) procedures between both networks, which can be achieved thanks to a flexible framework offering multiple authentication procedures. An example could include a mobile User Equipment (UE) accessing a WiFi hotspot.

b) Intersystem Service Access
The cooperation between the networks is closer due to a centralized billing and authentication functions. However, it does not offer a handover so the services in progress are dropped while switching between the two networks. In the example scenario, services offered by both networks could be used simultaneously.

c) Intersystem Service Continuity
Referred also as tight coupling, this model supports inter-RAT mobility management and requires both networks to interact in a tight way, such that a user is guaranteed a continuous service after a vertical handover. However, delays may be experienced.

d) Intersystem Seamless Service Continuity
Finally, this is the highest degree of interworking providing seamless handover between the RATs. It requires a very low latency and therefore, fast end effective mechanisms are needed on the link and network layer. These include network discovery procedures in particular for single radio terminals[2], pre-authentication schemes, efficient radio resource management and information exchange. The very tight coupling enables such features as load balancing between the two RATs.

[2]The terms *UE* and *terminal* are used interchangeably throughout this thesis.

A similar approach to differentiate the levels of network coexistence proposed in [23] was a modular cooperative concept based on common RRM and Generic Link Layer (GLL) [26], which is a universal layer for all the cooperating RATs. GLL provides a set of necessary functionalities, e.g., dynamic scheduling, and this way enables the convergence of RATs.

As indicated, LTE provided the possibility to interconnect with both 3GPP and non-3GPP wireless access in Release 8. Nevertheless, the work on integration with WiFi is still ongoing and latest initiatives include IEEE 802.11u amendment [27], which facilitates automatic and seamless connectivity to WiFi hotspots, thus significantly improving the user Quality of Experience (QoE).

The extensive work in the interworking area presented above opens the list of tool set that are necessary to provide ubiquitous experience.

Radio Resource Management

Convergence of different wireless networks requires more efficient resource management and control procedures within the heterogeneous platform. An important challenge resulting from interworking RATs is the design of common functionalities to manage the multiradio environment, e.g., RAT selection and load balancing, especially for tighter types of coupling.

Several studies and projects were carried out to develop an RRM system that would cope with the diversity introduced by multiple RATs. To this end, different concepts were proposed over the years, including a reconfigurable multi-RAT BS adapting to user traffic type and selecting the best combination of serving RATs [28] and a number of management platforms for interworking systems [29–31].

The research on RRM systems has tended to solely focus on multi-RAT networks, including such aspects as RAT selection and load balancing. However, it has not considered the other types of network heterogeneity. Therefore, future management systems need to be redesigned to account for the new network resources such as optical or computational and deployment directions including, e.g., Self-Organising Network (SON) concept, where the networks are able to constantly adjust their parameters based on past and current observation of performance.

Always Best Connectivity

One of the major components of an interworking scenario is proper selection of the serving RAT and cell. A set of important requirements was defined under the term ABC, where a user is supposed to be always offered the best connection in terms of not only network resources and coverage but also device type or personal preferences [32]. This calls for an efficient network discovery and selection in a multi-RAT scenario, where multimode terminals support a variety of RATs and are able to switch between them in a seamless way thanks to advanced support for AAA and mobility.

Clearly, very tight cooperation among various RATs is required to achieve the goal of providing a ubiquitous service in line with the ABC paradigm. For this reason, an RRM system is highly needed to control the cooperating networks and help to assign the best RAT to the end user. The assignment should be performed seamlessly, i.e., without affecting or interrupting the ongoing service, thus offering the end-users ubiquitous experience. As mentioned before, full integration of various access networks is supported since 3GPP LTE Release 8. Network discovery is facilitated by Access Network Discovery and Selection Function (ANDSF) [22], whose goal is to assist the UEs to perform access network discovery in an efficient way. The information about available networks may be sent over a secure signalling connection by the entity in the so-called push mode, thus saving the battery life of UEs, or be retrieved by themselves in the pulling procedure [33].

Even though considerable research effort was put to address the challenges in the above areas, the research problems remain open today due to increase of network complexity driven by two more types of network heterogeneity, which are introduced in the following sections.

This thesis addresses the above challenge and proposes a new network resource management system aligned with the development directions of the mobile networks. The framework introduced in Chapter 2 allows management of different kinds of network resources and is compatible with the principles of SON and cognitive networks.

In this thesis, multi-RAT networks are considered to work in a very tight coexistence mode, thereby enabling synergistic cooperation. In order to ensure always best connectivity, a number of studies proposed and investigated a variety of optimisation procedures facilitating the optimal choice of RAT [34–36]. However, these proposals consider one-time optimisation scenarios and are characterised by heuristic features. Chapter 3 of this thesis reviews the current methods of serving cell selection in multi-RAT environment, and proposes and evaluates a new optimisation model addressing the current gaps.

1.1.2 Heterogeneous Networks

With the ever growing traffic in mobile networks [37], there is an urgent need to increase the network capacity and meet the user demands. One of the ways to achieve that is through further network densification and bringing the network closer to the user. Deploying more macro sites, however, is not an attractive approach, due to high Capital Expenditure (CAPEX) and Operational Expenditure (OPEX) costs that are related to such network upgrade. Therefore, deploying Low Power Nodes (LPNs) in the areas that experience much higher demands due to the high density of users, e.g., shopping malls or airports, is a much more feasible solution. These small cells, i.e., metro-, pico- and femtocells, overlay the macrocell and form the so-called HetNet that can greatly improve the coverage and capacity of a network [38]. A HetNet can be further extended with relay nodes or WiFi hotspots, which also makes it a multi-RAT network. Small cells create the opportunity to offload mobile traffic and equipping small cells with WiFi module offers even better traffic management.

Small cells can greatly boost the network capacity but this gain comes at the price of a number of challenges [39, 40]. Dense and very often uncoordinated deployment in case of femtocells makes the network management very complex and thus developing efficient SON mechanisms is a must. These autonomous procedures can for example coordinate interference affecting parameters in co-channel deployment [41], control coverage [42] or the energy efficiency related performance. As a result, a node can be automatically put into sleep mode during, e.g., low traffic hours [43–45]. Last but not least, one of the features that clearly differentiates small cells fromWiFi hotspots, which is support for mobility,

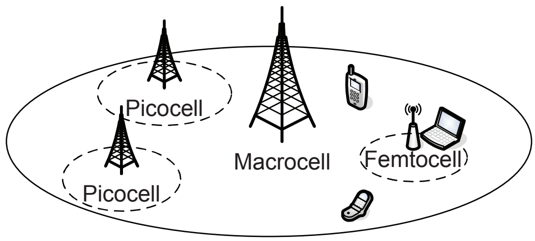


Figure 1.2: A HetNet example.

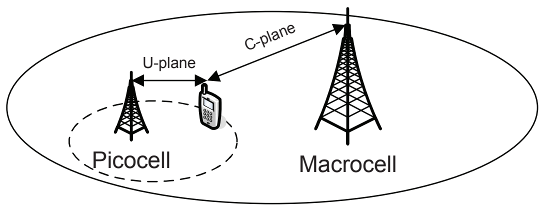


Figure 1.3: Control and user plane split in HetNets.

poses many problems in the new scenario [46]. Much higher number of cells in a given area significantly increases the number of handovers and cell (re)selections. Since the coverage of LPNs is much smaller than macro sites, it creates a threat especially towards cell edge and high mobility users resulting in increased signalling and degraded performance, e.g., ping-pongs, handover and Radio Link Failures (RLFs).

A very recent proposal of a new HetNet architecture is based on the functional split of Control Plane (C-plane) that transmits system and connection related signals and User Plane (U-plane) that handles user data [47–49]. In this scenario, macrocells are responsible for the C-plane for the UEs of their underlying small cells, which provide the data connection to the users as schematically shown in Fig. 1.3. In this new architecture, the cell (re)selections are controlled by the macrocell. As a result, the proposal has very important implications for tackling the mobility problem described above, and will thus help to significantly improve the success rate of mobility events. To date, however, the architecture is at its infancy stage and further research is needed to quantify the foreseen gains.

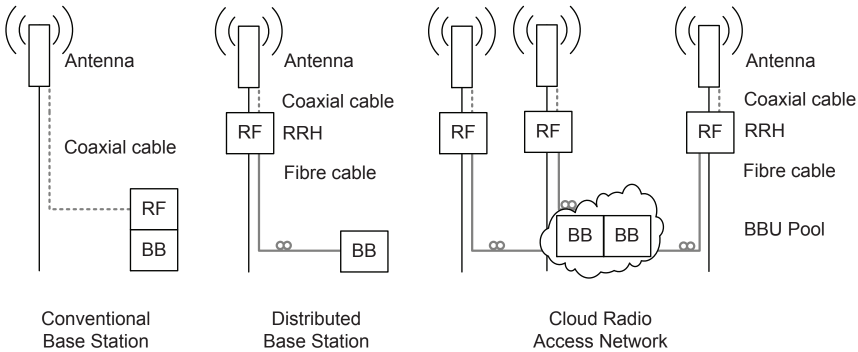


Figure 1.4: Base station evolution.

One of the goals of this thesis is to study the new HetNet architecture introduced above, investigate its feasibility and evaluate benefits in terms of mobility and energy efficiency. The analysis is presented in Chapter 4.

1.1.3 Base Station Architectures

Besides huge capacity demands, the operators face nowadays another significant challenge, which is the increasing cost related to network deployment, operation and maintenance. Parallel operation of various RATs as well as the growing number of sites to a great extent contribute to OPEX. The data traffic in mobile network constantly increases, and with flat rates the operators' goal is to reduce the cost per bit whenever possible. Within a mobile network, it is the BS that generates the most expenses due to such factors as cooling, site rental and signal processing and it has been the main focus for cost reduction [50, 51]. Therefore, in recent years there has been an increasing interest in new BS architectures that will bring the cost of running mobile networks down and reduce the deployment costs of wireless access. Fig. 1.4 presents the evolution of BS architecture from a conventional, through Distributed Base Station (DBS) to the newest proposal of Cloud Radio Acces Network (C-RAN). A clear separation of RF from BB processing is observable.

Conventional Base Station

The most common in today's mobile infrastructure are the conventional BSs, where an antenna mounted on a mast or a rooftop is connected to the RF and Baseband Unit (BBU) over a coaxial cable. The processing units are stored either under the BS tower or inside a building. The coaxial cable connection introduces high power loss which in turn results either in degraded performance or increased power consumption. Therefore, there has been much industrial interest in addressing these issues. The proposed solutions include more energy efficient hardware, e.g., smart cooling systems based on renewable energy sources [52], and new BS architectures described below.

Distributed Base Station

In order to mitigate the losses and costs introduced by the coaxial cable in conventional BS, vendors proposed a more distributed architecture where RF unit is placed much closer to the antenna in the form of a Remote Radio Head (RRH) that performs the analogue processing. This way the lossy coaxial connection is much shorter and the connection from the RRHs towards BBU is provided through an optical link and can be realized using, e.g., Common Public Radio Interface (CPRI) [53] or Open Base Station Architecture Initiative (OBSAI) [54–56]. This architecture offers much higher deployment flexibility, since the antenna location is to a less extent constrained by the site location or length of the coaxial cable as in the conventional centralized approach.

Cloud Radio Access Network

A step further towards lowering the costs associated with RAN can be taken by aggregating BBUs in one physical location forming a so-called BBU pool. In the Clean, Centralized C-RAN approach, many BBUs can be shared among various BS sites. Since the individual BS are dimensioned according to the peak traffic hours, because of sharing the number of BBUs can be lowered when compared to DBS [50,51,57]. This architecture brings a number of other immediate advantages. Thanks to centralisation, the cost of site rental and energy consumption, as well us network upgrades can be significantly reduced. C-RAN supports multi-

RAT networks and gives the possibility of connecting LPNs as well, thus demonstrating very high degree of flexibility and facilitating network scalability. Common processing aids the functionalities that require tight cooperation among BSs, e.g., handovers, Multiple Input Multiple Output (MIMO) or Coordinated Multipoint (CoMP). However, it requires a very good connection in the fronthaul, i.e., the link connecting RRH with BBU. The requirements are that data rates should be above 10 Gbps and latency lower than 0.5 ms [58]. Another important challenge concerns the virtualisation of BBU pools and sharing strategies among different BSs sites, RATs and operators.

The variety of BS architectures provides the mobile operators flexibility when addressing particular deployment requirements. It needs to be remembered though, that it also introduces another level of network diversity and should be regarded when managing the overall network resources.

Different types of BS architectures are considered when designing a generic network resource management system which is described in Chapter 2. This requires taking into account not only radio, but also optical and computational resources needed for BB processing, as introduced in C-RAN.

Furthermore, since resource centralisation and virtualisation is a distinctive feature of C-RAN, it is important to analyse the influence of resource sharing on the network performance as well as evaluate the benefits of the individual partners sharing the pool of resources. This thesis provides such an analysis in Chapter 5.

1.2 Thesis Structure

This thesis addresses major technical challenges in the three interconnected research areas outlined above. The overall thesis scope and particular areas of focus in every chapter is illustrated in Fig. 1.5. This figure also indicates the Ph.D. publications that chapters are based on.

This thesis has been divided in seven chapters. Based on the definitions and introduction given in Chapter 1, Chapter 2 gives an overview of RRM functionalities and platforms designed for multi-RAT systems.

It presents a novel generic network resource management framework applicable to all types of network heterogeneity as discussed in the Introduction. Moreover, it allows for a unified management of all types of resources, including radio, optical and computational. The framework covers also SON and cognitive networks and example interworking architectures are discussed.

Chapter 3 focuses on a specific aspect of RRM for such multi-RAT platforms, which is optimal cell selection and providing always best connectivity. A new joint optimisation model for cell selection and resource allocation is proposed. The model adopts a double objective function and takes into account handover decision dimension. This way it mitigates the heuristic character of the existing solutions. The performance performance evaluation is provided through joint simulation and simultaneous optimisation.

Chapter 4 shifts the focus towards HetNets by introducing the concept of dual connectivity. A description of the new architecture together with an implementation proposal is discussed. Furthermore, feasibility of the new approach is studied and evaluated using an example soft-pilot signal and a proposed Integer Linear Programming (ILP) formulation for an optimal assignment. Since the new architecture facilitates mobility management and energy efficiency, potential gains in these two areas are also discussed.

In Chapter 5, cellular systems with shared resources, e.g., C-RAN are analysed. A cellular network is modelled as a circuit switched network with direct routing. The influence of the degree of sharing on the network performance is investigated for various network dimensioning strategies. A quantitative study is performed and the benefits of individual partners are evaluated.

Finally, Chapter 6 concludes this thesis. The main results and contributions are summarized and future research directions are indicated. Furthermore, the emerging concept of Fifth Generation (5G) is characterized. New technologies that could potentially enable 5G networking are presented and reviewed together with the research and development trends.

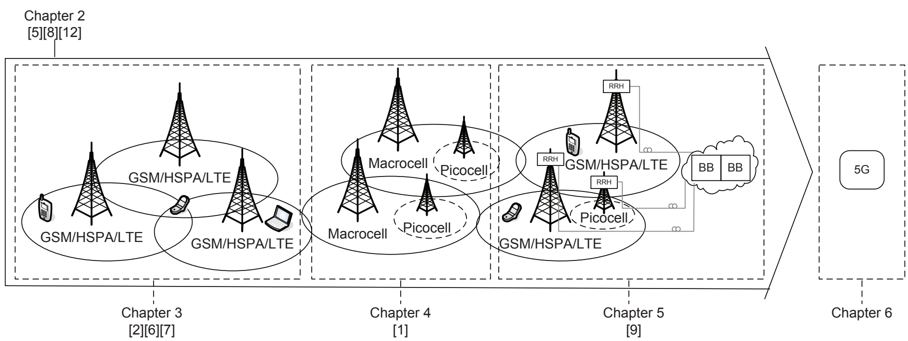


Figure 1.5: Thesis overview.

Chapter 2

Network Resource Management

This chapter sets the background for network resource management and introduces a novel universal approach to design a management system. The proposed framework can be applied to any type of heterogeneous network, like multi-RAT or HetNet and supports the new functionalities of LTE-A such as CoMP, Carrier Aggregation (CA) and enhanced Intercell Interference Coordination (eICIC). It is also BS architecture independent and is therefore applicable to conventional, DBS and C-RAN deployments.

This chapter is organised as follows: After a brief introduction, an overview of related work is given in 2.2. In Section 2.3 new requirements towards management systems are discussed. Section 2.4 presents the proposed management framework, and demonstrates its applicability to all types of considered network heterogeneity. Furthermore, enhancements taking into account features of SON and cognitive networks are presented. In 2.5 an example implementation of the framework in an multi-RAT network is shown and evaluation considerations are covered in 2.6. Finally, the chapter is summarized in 2.7.

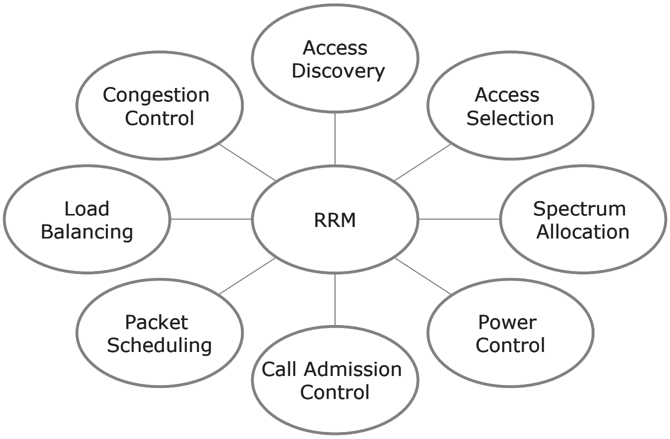


Figure 2.1: Radio resource management functionalities.

2.1 Introduction

The role of an RRM system is to ensure proper operation of a RAN by efficient use of radio resources while meeting user demands and guaranteeing requested QoS. Figure 2.1 shows the core functionalities of such systems, starting from network discovery and cell selection, through resource and power allocation, packet scheduling to congestion control and load balancing [59].

Coexistence of various network technologies and architectures facilitates cooperation and joint management of resources. Consequently, it leads to a better performance of a network as a whole, when compared to a set of individual contributors. Hence, these functionalities are at the same time important areas of research in wireless networking.

2.2 Related Work

Cooperative RRM systems are designed to control coexisting multi-RAT networks, and their particular functionalities depend on the level of coupling between different networks. Most of the existing systems, such as Common Radio Resource Management (CRRM) [30] which was developed within the EVEREST project [60], Joint Radio Resource Management (JRRM) [29] or Multi-access Radio Resource Management (MRRM) [31] [61] were proposed in a transition time when new RATs such as GPRS, EDGE and UMTS started to be rolled out. Therefore, they considered only one type of network heterogeneity based on multi-RAT.

The first two of the aforementioned systems are centralized which makes them very difficult to implement, as they are characterized by high latency and excessive signalling. CRRM introduces a two-level hierarchy, where one local RRM entity is responsible for one cell, whereas higher management entities, more central, coordinate the actions within a number of cells. The degree of interaction and coupling between the two layers are implementation specific. Naturally, the tighter the cooperation, the better the results of joint management and optimisation over a set of underlying cells.

The core concept behind JRRM is service splitting and simultaneous connection to two RATs. In this set-up, the data is cooperatively delivered through both systems exploiting their advantages, for example stable coverage and high data rates of 3G and WiFi, respectively. Both traffic streams are managed in a joint way.

On the contrary, MRRM proposed a more distributed approach using a set of cognitive agents. Another cognitive management concept based on Software Defined Radio (SDR) was introduced in the ARAGORN project, where the entities can access all the network layers and perform management decisions with the help of an integrated optimisation toolbox [62].

2.3 Management Challenges

As presented in Chapter 1 we are currently facing a new direction within mobile networks development. With the introduction of small cells enhancing network capacity, new BS architectures, as well as new network functionalities, network resource management has become much more complex. New network management challenges can be divided into two groups:

a) architectural, such as multiple tiers introduced by small cells and new BS concepts,

b) functional, related to new features like CoMP,CA and eICIC in LTE-A.

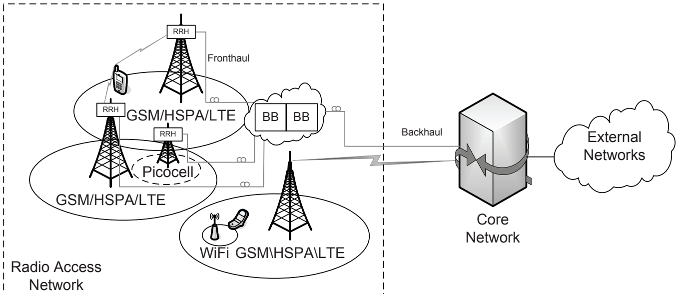


Figure 2.2: RAN management scope.

The scope of a network management system is illustrated in Fig. 2.2, where the RAN is shown in more detail when compared to other parts of the network architecture. The figure presents its complexity resulting from heterogeneity of mobile networks nowadays. Therefore, as discussed before, because of only a multi-RAT approach, previously proposed platforms can not fulfil the new requirements entirely.

However, some of their features can be adopted to the new management frameworks, for example multihoming where a terminal is connected to many RATs at a time (as proposed in JRRM) or the concept of cognitive agents dealing with local optimisation (as in MRRM). Furthermore, due to a significant number of small cells, there is a high need for cognitive network behaviour and management automation employing SON mechanisms, as most of the Home eNodeBs (HeNBs) are out of the operators' control. Moreover, recent developments have heightened the need to consider a multitude of network resources. It is not only scarce radio spectrum that needs to be managed carefully, but also, e.g., optical and computational resources introduced in the new C-RAN architecture.

2.4 Management Framework

Resource management algorithms have various scope and time span depending on the entity and functionality they act upon. Hence, we propose a novel approach to resource management by introducing a division of different management levels based on the time needed to perform certain control actions. In the general concept of such a structure four levels are distinguished:

a) Ultra-fast: actions at millisecond time scale,

b) Fast: actions that need seconds to take an effect,

c) Slow: less frequent actions happening in minutes/hours.

d) Ultra-slow: global actions performed very rarely, often within days or months, usually requiring manual operation.

By *ultra-fast* and *ultra-slow* term the fastest and the slowest stages are denoted. The granularity of the levels is flexible, depends on the implementation preferences and network deployment, and is operator specific. One may introduce additional levels, as for example *super-fast*, if necessary.

2.4.1 Resource Diversity

As mobile networks are enhanced with new features and new architectures are being proposed, new resource management schemes need to be developed as well. The new framework should also take into account other types of resources besides radio, which makes designing a universal resource management platform even more challenging. The framework presented above is applicable to a number of different network resource types, including:

a) spectral,

b) optical,

c) computational.

The framework allows treating network resources globally, as they are tightly interconnected and for instance a decision in the radio domain may affect the optical part of the network.

Management of radio resources was introduced at the beginning of this chapter. In the DBS and C-RAN fronthaul, i.e., the connection between an RRH and a BBU, poses numerous challenges. It requires a very fast interface with low latency to handle transmission of BB signals. Ensuring enough resources for fronthaul and backhaul is a deployment and maintenance task.

Lastly, managing processing power within a BBU pool is one of the key challenges posed by the new C-RAN architecture. Proper network dimensioning leading to optimal utilisation of computing resources and allowing scalable upgrades becomes one of major network design steps. Since all the resources within the pool are shared among all connected RRHs, virtualisation of the processing units and their dynamic allocation to RRHs to deal with the changing load and traffic patterns is needed in real-time.

2.4.2 Management Functionalities

As introduced above, four levels of management granularity are proposed. Fig. 2.3 illustrates a time-scale along with some selected corresponding resource management procedures. For example scheduling along with CoMP needs to be performed on a millisecond basis whereas network planning and maintenance are more long-term actions. Let us note, that the division is not explicit as some of the functionalities are very flexible in time, for instance a network fault may take from hundreds of milliseconds to even days to be recovered [63], depending on its type and importance. Antenna tilting represents a similar case, as it may be done very fast if controlled electrically or slower when it requires manual operation. The functionalities in Fig. 2.3 are placed along the time-scale in a way that represents average timing required for a specific management task [58, 64–67].

2.4.3 Self-organising and Cognitive Aspects

Due to increasing network complexity with new RATs, network architectures, and multiple cell tiers, network management has become very complex and it is one of the major challenges in mobile networks. To aid that SON has been introduced to LTE in Release 8 [68] and its goal is to automate most of the management procedures so as to make it faster and lower the cost of operation. SONs have three distinctive features:

a) self-organisation,

b) self- optimisation,

c) self-healing.

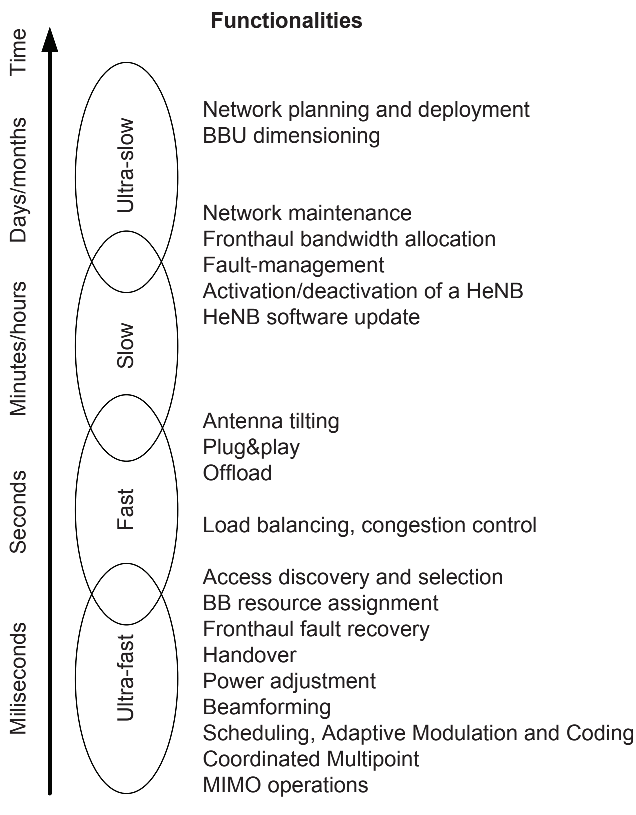


Figure 2.3: Management functionalities in time.

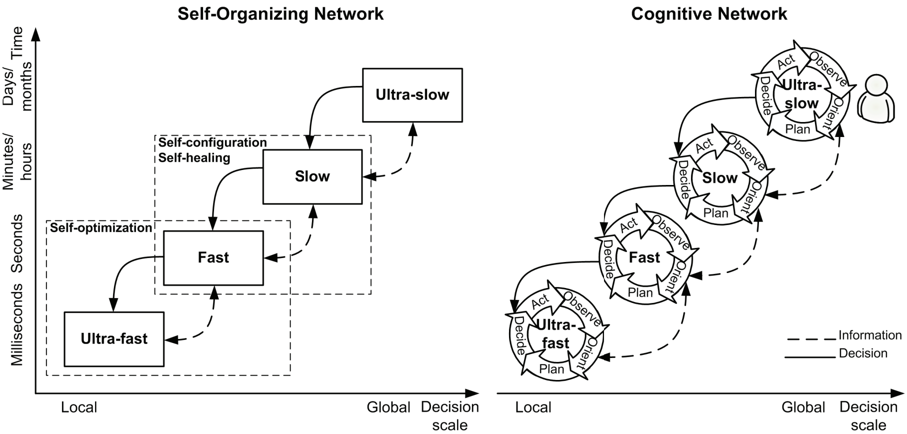


Figure 2.4: Management framework integrating SON and cognitive properties.

A number of different algorithms can be implemented to support SON behaviour, for example those responsible for load balancing or coverage optimisation. If resource utilisation in a cell becomes too high, it triggers a handover for some connections so as to move them to a neighbouring cell. Similarly, if too high interference is detected, a BS may adjust its transmission power. These procedures can be performed in all the cells leading to a more uniform traffic distribution and improved network coverage.

Basic processes of SON, namely self-configuration, self-healing and self-optimisation fit into our general framework, as illustrated on the left side of Fig. 2.4. Self-configuration and self-healing, depending on configuration complexity and fault importance, can be done at fast or slow level, whereas self-optimisation is more applicable at ultra-fast and fast speeds. As indicated in the figure, the scale of a decision increases with the time that it takes. Very local actions are planned and performed instantly and need to take an immediate effect. On the other hand, decisions that have impact on more network entities require longer planning and execution time.

Modules at different levels are connected via communication links enabling information exchange that facilitates taking the management decisions. For example in order to perform load balancing, a management entity would need the information about the level of cell/sector/neighbour load, available tiers (macrocells, pico- and femtocells), type of access (open/closed subscriber group) and terminal capabilities. The modules are then able to perform reasoning and decide upon certain actions, such as the Mobility Load Balancing (MLB) mentioned above or Mobility Robustness Optimisation (MRO) aiming at minimising RLFs and limiting the number of handovers that may lead to ping-pong effect. Management decisions can be executed locally or sent to a lower layer module as indicated in Fig. 2.4. Therefore, modules can act as both, Policy Decision Point (PDP) and Policy Enforcement Point (PEP) depending on whether they take and send the decision or execute it following the instructions of other modules.

The general network management trend is to automate as many procedures as necessary and make them time and cost efficient. From this perspective, SON may be slow in adapting to dynamically changing conditions, as it may require manual updates of the algorithms. The next step in self-organisation is introduced by cognitive approaches [69], where management modules are able to learn based on current and past observations. This way self-organisation is not limited by the predefined algorithms and a system is able to adjust to any unexpected situations.

The cognitive concept when adapted to network management may be much more beneficial in case of so complex multi-RAT, multi-tier networks. A cognitive cycle distinguishes five phases, namely observe, orient, plan, decide and act. As indicated on the right side of Fig. 2.4, each autonomous module can employ cognitive behaviour. Based on the observed network state as well as the information retrieved from different management entities in the orientation phase, the cognitive process can be started. The management entity is able to intelligently adapt to the current conditions and learn from similar situations in the past, since the system has a learning ability. As a result of cognitive reasoning, management decisions supporting the system can be planned and taken. It is important to carefully design the decision cycle, so that the system adapts to the dynamic nature of the traffic and avoids extensive signalling but at the same time ensures optimal operation [70]. As shown in the figure, these decisions can be executed locally or be sent to other layers as suggestions and recommendations directly entering the decision phase of an underlying module. The importance of human cognition and manual operation in network management at the ultra-slow level is also emphasized.

Recently a new docitive approach has been introduced [71], where network nodes have also a teaching ability. By implementing machine learning algorithms, they are able to exchange information and teach each other which accelerates their learning process and leads to faster convergence.

2.4.4 Inner Module View

The internal architecture of a management module is depicted in Fig. 2.5, where clear adoption of the cognitive behaviour is visible. The module can interact with its superior, inferior, as well as modules at the same hierarchical level to exchange the status information. Reports and updates from the neighbours facilitate the orientation phase of the cognitive cycle. This data is used for further analysis, comparison with previous records and preparation of future prognosis. Based on its own past observations, status of other modules and finally current network performance with regard to managed resources, the module takes a decision following the implemented algorithms. Each module can act upon settings and parameters using certain procedures within its own area of responsibility, e.g., lower the transmission power. As a result, network performance can be improved according to the required thresholds, e.g., load, utilisation and energy consumption limits.

Another important aspect is the coordination between the modules. Every module should execute changes on its own but at the same time be aware of the configuration updates introduced at the neighbours, as it may influence its own decisions and consequently performance. Some of the decisions can be taken simultaneously and conflict upon execution, e.g., putting a small cell into sleep mode. We proposed a Carrier Sense Multiple Access (CSMA)-based solution [9], where the idea is to inform all the neighbouring modules about the planned actions. If a potential conflict occurs, i.e., two modules receive their notifications, it is resolved by introducing a random back-off period. During that time, all the potentially conflicting modules continue the cycle by entering the observation and orientation phase.

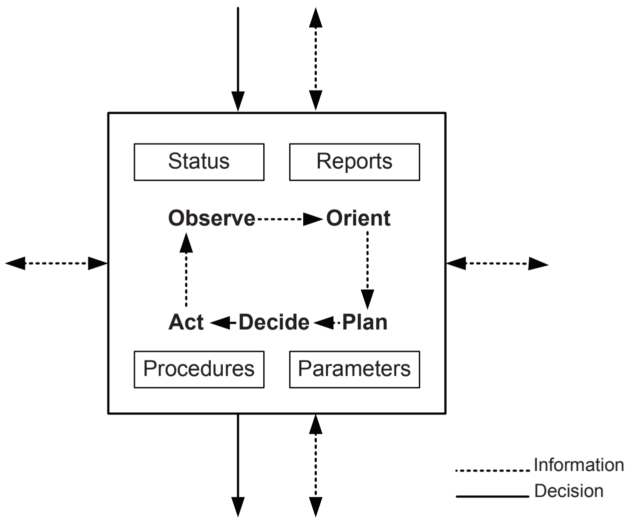


Figure 2.5: Inner module architecture.

2.5 Multi-RAT Network Management Perspective

The proposed framework is characterized by a high level of flexibility and can be applied to a number of network scenarios. Such a management model can be deployed in a network with conventional macro BSs, as well as DBS, and finally C-RAN. Moreover, it is RAT and network architecture independent and therefore it can operate also during migration phases of network evolution.

Fig. 2.6 shows how the platform can be developed within a single RAT and presents an example of an inter-RAT cooperation in terms of management. The entire structure resembles a tree with 1:N mapping, where lower branches can be controlled by the modules placed on a higher layer and exchange information with their superior and inferior modules. At the middle level of module hierarchy (fast and slow in this case), a flat horizontal structure is proposed. Here information is shared among modules of the same layer with no master control point having a centralized database. A more detailed top-to-bottom description of particular layers is given below.

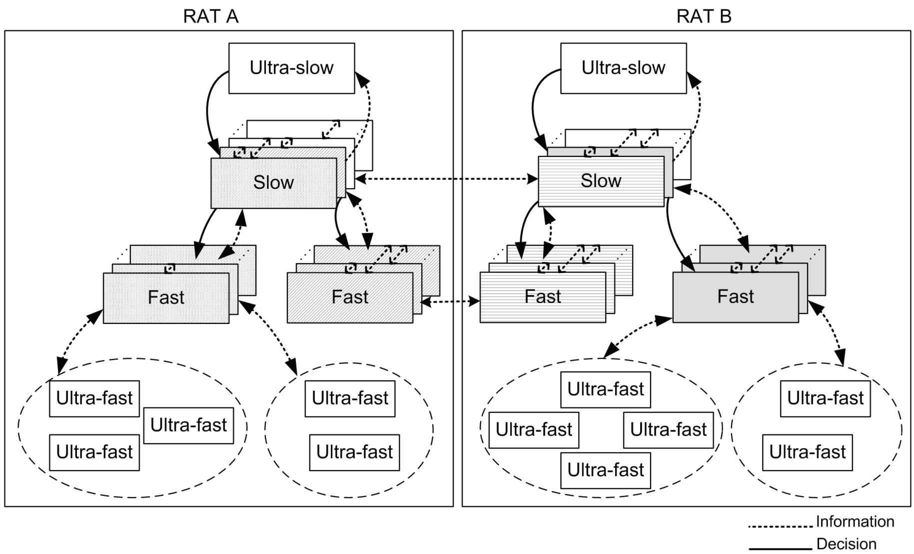


Figure 2.6: Inter-RAT management cooperation

Ultra-slow modules

The highest modules in the hierarchy are responsible for long-term management decision such as network planning and deployment or dimensioning of BB processing units in C-RAN. Due to mainly manual operation, any decision can be sent down the management tree to trigger and enforce particular network reaction, such as software updates.

Slow modules

These modules have access to the information from higher and lower layers (ultra-slow and fast) while taking management decisions. Each module controls a few underlying fast modules and has only one superior ultra-slow module, as indicated with shading in Fig. 2.6. They are also capable of exchanging network information in a horizontal manner, even between RATs. For example, HeNB deactivation/activation decision can be made after retrieving the load and utilisation information from the underlying fast modules, as well as consulting network parameters with neighbouring slow modules.

Fast modules

Similarly, as for slow modules, there is a number of lower layer entities (ultra-fast modules) and only one corresponding higher layer information point (slow). Furthermore, fast modules are connected with the neighbouring fast modules for horizontal information exchange. As depicted in the figure, this can also support inter-RAT communication facilitating, e.g., load balancing decisions. In case of congestion some traffic may be redirected through a forced handover to a neighbouring BS, another RAT or offloaded to WiFi.

Ultra-fast modules

Placed at the bottom of the management tree ultra-fast modules control the fastest procedures in the network resource management, e.g., scheduling. For this reason they do not communicate with other ultra-fast modules, as this would be too time consuming and also lead to significant signalling. They are able to adopt decisions and suggestions from higher layers. It may be possible that one module is responsible for more than one BS or BB processing unit, if they are located in close proximity or deployed within C-RAN to facilitate CoMP processing for example.

2.6 Evaluation Considerations

The proposed hierarchical network resource management framework is locally distributed, as the information exchange is facilitated only among neighbouring modules. This is a compromise between a centralized approach with the detailed knowledge about the network but excessive signalling and a distributed one, where there all the modules act independently of each other. In the proposed approach modules with specific responsibilities can be more responsive and react faster to constantly changing wireless environment and traffic load when compared to multi-functional modules. However, it would be valuable to perform a detailed evaluation of the signalling among the modules paying special attention to decision propagation delay in the horizontal and vertical communication direction.

This requires a definition of specific target scenarios, and one of the representative cases could consider inter-RAT management as presented above. System level simulation should consider a variety of network deployments, traffic profiles as well as particular RATs. To limit the test-scenario, load balancing could be used as it requires implementation of ultra-fast and fast modules with the related functionalities.

This could help assess the feasibility and advantages of the presented approach and provide some insights into the management system performance.

2.7 Summary

This chapter has presented the fundamentals of RRM and explained the importance of joint management of other types of resources besides radio, such as optical and computational. A novel approach to overall network resource management addressing all types of network heterogeneity was presented. In the proposed framework system functionalities are hierarchically divided based on the time needed to perform the management actions.

Hierarchical structure requires careful design and organisation of a management system and needs to take into account the network architecture, i.e., connections between particular modules. On the other hand clear arrangement allows for better control over management actions. Furthermore, it ensures better synchronisation especially when considering joint resources, e.g., wireless and optical simultaneously. Individual modules can keep their integrity and act in a cognitive manner and at the same time maintain a connection to a higher and lower placed modules. In this way they can obtain more general or more detailed information about the system performance that facilitates the internal decision of a module.

This proposed network resource management is a generic scheme covering numerous scenarios. Characterized by high flexibility, it is applicable to a wide variety of network deployments including multiple RATs, HetNets and different BS architectures such as DBS and C-RAN. Furthermore, the platform can be enriched with SON and cognitive network properties, thus leading to more universal, automated and efficient network resource management.

Chapter 3

RAT Selection in Multi-RAT Networks

In this chapter more attention is paid to particular functionalities of an RRM system. Due to highly overlapping coverage of various access technologies, RAT selection and resource assignment in multi-RAT networks is of interest and a novel optimisation model is proposed. The model adopts two objective functions, maximising the number of served users and the minimum granted utility at once. Furthermore, handover is included as an additional decision dimension. The model is evaluated using simulation with concurrent optimisation.

This chapter is organised as follows: The next Section discusses the motivation behind this work, Section 3.2 presents the problem of RAT selection and resource allocation more in detail whereas Section 3.3 introduces the proposed optimisation model. Section 3.4 discusses the simulation set-up used for evaluation purposes including network architecture and utility function. Simulation results are presented in Section 3.5 and finally Section 3.6 concludes this chapter.

3.1 Introduction

When analysing the statistics of mobile subscriptions by technology, one can observe the dominance of GSM/EDGE mobile standards, followed by Wideband Code Division Multiple Access (WCDMA)/HSPA and cur-

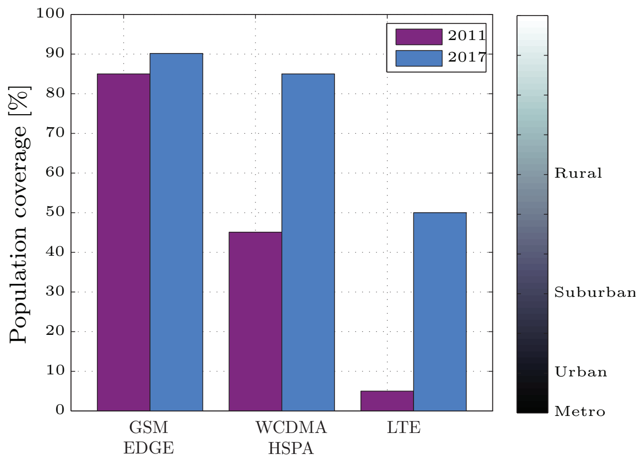


Figure 3.1: Population coverage in 2011 and 2017- based on [15].

rently under deployment LTE. In the near future, as forecasted in [15], the presence of LTE and WCDMA will significantly increase. LTE, in particular, will become common in metro and urban areas. Widely available EDGE will maintain its overall coverage, whereas HSPA will increase its availability steadily and cover also most of the suburban and rural areas as shown in Fig. 3.1.

As highlighted in Chapter 1 a number of different RATs available in the wireless environment forms a multi-RAT network with highly overlapping cells. This mixture of technologies is able to bring a ubiquitous service to end users equipped with multimode UEs that are capable to switch between technologies in a seamless way. In order to fulfil the requirements of the ABC paradigm [32], three conditions must be satisfied:

1. tight cooperation between the RATs enabling exchange of control information,
2. seamless handover so that a UE can smoothly switch between the technologies and stay connected anytime and anywhere,
3. optimal selection of the RAT and assignment of radio resources.

The last issue is the core topic of this chapter under an assumption that the first two conditions are met.

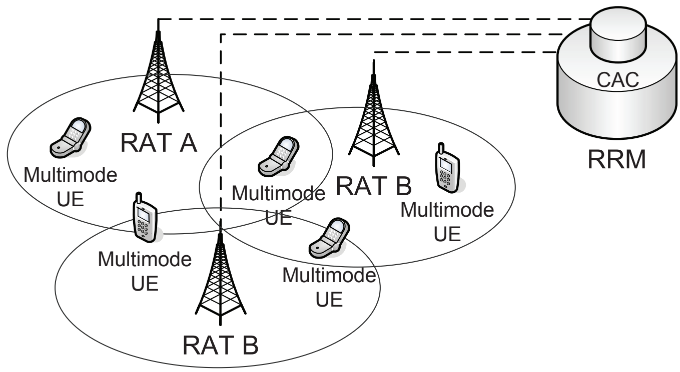


Figure 3.2: Network-centric RRM with CAC.

3.2 RAT Selection in Multi-RAT Networks

To provide seamless ubiquitous service, very tight cooperation between the network entities of different RATs is required. Chapter 2 presented RRM systems facilitating such cooperation. In CRRM [30] or JRRM [72] common or joint network entities implement all the actions regarding the overall multi-RAT network control. Call Admission Control (CAC), as an RRM entity common for a number of RATs and/or cells, sets up and manages the connections for all the UEs under its area of responsibility, as shown in Fig. 3.2.

The module gathers and maintains all the necessary information about the UEs, such as their capabilities, signal quality reports, required service type, radio parameters etc. It has also access to the characteristics of BSs that are present in its control region, such as the number of available resources and the inter-RAT configuration information. All this data is used in the process of assigning UEs a serving BS, RAT and sufficient number of resources, with the goal of achieving overall efficient utilisation.

Depending on the management system implementation, the entity responsible for call admission control and resource allocation can serve a number of cells and manage a certain area more globally for centralised RRM systems or locally if it is a more distributed platform. For example this entity could be used in the management of future networks based on the C-RAN architecture [51] and can then reside as a module in the BBU pool and control the connections of UEs to particular RRHs.

Referring to the network resource management model proposed in Chapter 2, RAT selection and resource allocation algorithm or optimisation model could be implemented at the fast level according to the time-scale presented in Fig. 2.3. In this way, the assignment procedure can be invoked periodically and its results sent down the decision tree to the super-fast modules, that are responsible for scheduling. As discussed in Section 2.5 ultra-fast entities are able to follow and adopt recommendations from their superior modules.

Resource management modules exploit the knowledge about a bigger part of the system than just a single BS. The joint modules are usually also more powerful and able to handle more complex processing, such as online optimisation.

3.3 Optimal Assignment

This chapter focuses on designing and evaluating an optimisation model that can support management entities responsible for RAT selection and resource allocation in their decisions. First, the problem is described by means of graph theory and a heuristic proposal is presented. Next, related work focusing on designing an ILP formulation is discussed and finally, a novel optimisation model is described in detail.

3.3.1 Graph Theory Approach

In the RAT selection problem, two disjoint sets can be distinguished, i.e., BSs and UEs. Therefore, the mobile network can be represented as a bipartite graph. Let us then consider a bipartite graph $G = (B \cup T, U)$ with the sets defined as follows:
$B = \{1, 2, ..., b\}$ is a set of BSs operating in one of the RATs
$T = \{1, 2, ..., t\}$ is a set of multimode terminals
U is a set of utility values u_{tb} describing suitability of a connection of UE t to BS b.

A matching is a collection of the edges of graph G so that no two edges share a vertex. An example of a system consisting of $|B| = 4$ BSs providing service to $|T| = 7$ UEs is depicted in Fig. 3.3 where one of the possible matchings is marked in bold.

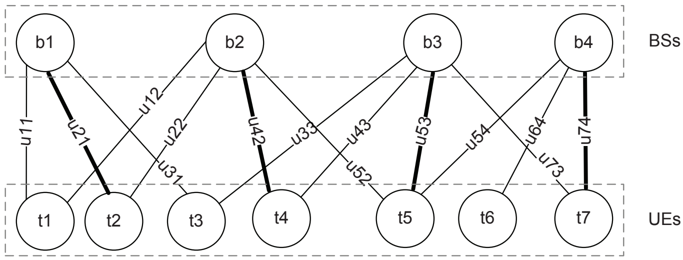


Figure 3.3: Example bipartite graph with a matching.

If a BS was allowed to serve only one terminal, this would be a classic general assignment problem [73], and the task would be to find a matching. Depending on the objective function, different algorithms may be used to find matchings in bipartite graphs. If the number of connected UEs is to be maximized, Hopcroft-Karp algorithm [74] would be the best choice, as it finds maximum matching in a bipartite graph at the cost $O(m\sqrt{n})$, where m is the number of vertices and n represents edges. On the other hand, if a weighted bipartite graph is considered as in Fig. 3.3, the Hungarian algorithm [75] would provide the fastest solution at $O(n^3)$.

However, it is not the case since multiple assignments to a BS are allowed. A problem arises, as usually the two sets are of not equal cardinality $|B| \neq |T|$. A BS b serves more than one UE, which contradicts with the definition of a matching, and a new method needs to be applied.

To address this issue we proposed a recursive approach to terminal-BS assignment [8]. In this way, matchings found in the consecutive rounds can be combined to form the final solution of the problem. The algorithm starts with an empty matching which is gradually updated with the solutions of the adopted matching algorithm, e.g., Hopcroft-Karp. The procedure is executed recursively until all the terminals are assigned to a serving cell or no more matchings can be found in the remaining subset (all the resources have been assigned).

3.3.2 Existing ILP Models

Although several optimisation models were proposed to solve the problem of the RAT selection in a multi-RAT environment [34–36], considerable research efforts are needed to mitigate their one time optimisation character.

More specifically, the existing models solve the problem for a scenario belonging to a consecutive set of snapshots. However, they do not analyse the relation between the snapshots. Therefore, when comparing the assignment between two consecutive time slots, it may appear that even though the problem is solved to optimality for both of them, applying these solutions to a network will require many assignment changes between the time slots resulting in multiple handovers. If longer period of time is observed, this may result in a ping-pong effect which consists of frequent assignment changes of UEs that are highly mobile or close to a cell border. Hence, it is crucial to optimise the assignment not only for a single time slot but also consider longer perspective.

Furthermore, some of the existing models demonstrate heuristic behaviour. For instance in [36] if the available radio resources are not sufficient to satisfy the requests of all the users, some of them may be dropped according to a priority list established in advance. Once the number of users is reduced, the problem is resolved but it may take several such attempts until a feasible solution is found. It is important to solve the optimisation problem at once to avoid unnecessary delays, waste of computing resources and ensure smooth network operation.

3.3.3 Proposed ILP Model

In this section, a new optimisation model and solution algorithm for RAT selection and resource allocation in multi-RAT networks is presented. As discussed above, even though the problem has been extensively studied, the proposed solutions have serious drawbacks. Here, we introduce a new model addressing these issues by adding handover as an additional decision dimension and analysing two consecutive time slots in the optimisation procedure. Moreover, introducing penalty for handover occurrence, the model aims at maintaining more stable connections and allows for an efficient utilisation of resources at the same time. Furthermore, the proposed model overcomes the heuristic character of the existing ones and thanks to a novel ILP formulation automatically regulates and selects the users to be served. There is no need for a repetitive list generation and selection, which leads to a better computational performance. Finally, the model considers two objective functions and aims at maximizing the minimum utility of the network and the number of served UEs.

Before discussing the model in detail, let us first describe its elements and the corresponding notation. A cellular network consisting of a set B of BSs that provide a telecommunication service to a set of UEs T is considered. Each BS $b \in B$ installs a set R of RATs and each RAT provides I resource units. A BS $b \in B$ offering services through a RAT $r \in R$ has a capacity of C_{br} that is limited by the number of resources I. The assignment of a quantity of resources to a UE represents a utility that reflects the assignment suitability to a given user. A UE is covered with service if it is assigned a subset of resources that guarantees its minimum required utility U^t_{min}. Similarly to [36], it is assumed that the utility gained by a user depends on the RAT and in general increases as the number of assigned resources increase. The utility value U^t_{bri} gained by a UE t is thus indexed over the BSs $b \in B$, the RATs $r \in R$ and the resources $i \in I$.

The RAT selection and resource allocation problem aims at assigning resources to UEs in order to serve the maximum number of users, while maximizing the minimum utility of the system, i.e., the goal is to maximize the lowest utility among all the connected users. The assignment decision considers the possibility of handover occurrence, therefore it takes into account the previous selection, and the network is observed at two consecutive time slots $p \in P = \{1, 2\}$. An additional goal of the model is to limit the number of handovers while providing connectivity, hence handover comes with a penalty for a UE $t \in T$ by a value of $w_t > 0$. Four decision variables are introduced to model all the decisions:

1. a binary *resource assignment variable* $y^{tp}_{bri} \in \{0, 1\}$, $\forall\, t \in T, b \in B, r \in R, i \in I, p \in P$, is equal to 1 if UE t is assigned i resources by BS b through RAT r in period p and equal to 0 otherwise,

2. a binary *service variable* $x_{tp} \in \{0, 1\}$, $\forall\, t \in T, p \in P$, is equal to 1 if UE t is served in period p and equal to 0 otherwise,

3. a binary *handover variable* $w_t \in \{0, 1\}$, $\forall\, t \in T$, is equal to 1 if UE t experiences handover and to 0 otherwise,

4. a single continuous *utility variable* $u \in [0, 1]$, represents the lowest utility gained by a served UE of the network.

The complete notation used in modelling the problem is summarized in Table 3.1.

Table 3.1: Notation

Parameter	Definition
$t \in T$	set of UEs
$b \in B$	set of BSs
$r \in R$	set of radio access technologies
$i \in I = 1, ..., \vert I\vert$	set of assignable units of resources
$p \in P = [1, 2]$	set of time slots
U^t_{bri}	utility value of UE t towards BS b and RAT r if i resources are assigned
U^t_{min}	minimum utility requirement of UE t
π_t	handover penalty for UE t
M	sufficiently large positive constant, $big - M$
y^{tp}_{bri}	resource assignment variable of UE t served by BS b through RAT r with i resources
x_{tp}	service variable of UE t in period p
w_t	handover variable of UE t
u	minimum utility value

The original optimisation model is the following:

$$\max u \tag{3.1a}$$

$$\max \sum_{t \in T} \sum_{p \in P} x_{tp} - \sum_{t \in T} \pi_t \cdot w_t \tag{3.1b}$$

$$u \leq \sum_{b \in B} \sum_{r \in R} \sum_{i \in I} U^t_{bri}\, y^{tp}_{bri} + M\,(1 - x_{tp}), t \in T, p \in P \tag{3.1c}$$

$$\sum_{b \in B} \sum_{r \in R} \sum_{i \in I} U^t_{bri}\, y^{tp}_{bri} \geq U^t_{\min}\, x_{tp}, t \in T, p \in P \tag{3.1d}$$

$$\sum_{t \in T} \sum_{i \in I} i\, y^{tp}_{bri} \leq C_{br}, b \in B, r \in R, p \in P \tag{3.1e}$$

$$\sum_{b \in B} \sum_{r \in R} \sum_{i \in I} y^{tp}_{bri} \leq x_{tp}, t \in T, p \in P \tag{3.1f}$$

$$\sum_{i \in I} y^{t1}_{\beta\gamma i} + \sum_{b \in B \setminus \{\beta\}} \sum_{r \in R \setminus \{\gamma\}} \sum_{i \in I} y^{t2}_{bri} \leq 1 + w_t,$$

$$t \in T, \beta \in B, \gamma \in R \tag{3.1g}$$

$$y^{tp}_{bri} \in \{0, 1\}, t \in T, b \in B, r \in R, i \in I, p \in P \tag{3.1h}$$

$$x_{tp} \in \{0, 1\}, t \in T, p \in P \tag{3.1i}$$

$$w_t \in \{0, 1\}, t \in T \tag{3.1j}$$

$$u \in [0, 1] \tag{3.1k}$$

The problem has a biobjective function and includes:

1. the maximisation of the lowest utility of a UE;
2. the maximisation of the difference between the total number of served UEs and the total penalisation coming from handovers.

The connection between the utility variable u and the utility gained by each UE is described by constraint (3.1c). This constraint is activated only when the included variable x_{tp} equals 1. If $x_{tp} = 1$, the presence of a sufficiently large value $M > 0$, the so-called $big - M$ coefficient, makes the constraint redundant [76, 77]. Adoption of the big-M constraint is an important improvement when comparing with the heuristic models like [36]. Here, if the number of UEs to be served is fixed, the served UEs are not chosen a priori from a list but the choice is done directly by the optimisation model. Constraint (3.1d) ensures that a served UE is guaranteed a minimum utility value so that its connection requirements are met. Constraint (3.1e) expresses the limit on the capacity C_{br} of BS b and RAT r and makes sure that it is not exceeded. An important model assumption is that a UE is allowed to set up a connection to only one BS/RAT at a time. Constraint (3.1f) imposes that a UE receives resources only if it is served. Finally, constraint (3.1h) controls the handover procedure: if a UE is served in both time slots and there is a shift in the BS -RAT assignment marked by (β, γ) between the two considered time slots, the handover variable w_t is forced to 1. Thanks to this approach, the model can be used for multiple consecutive time instances and support the decisions of cell selection modules within network resource management platforms.

Concerning the solution approach, a standard way to deal with a biobjective function is adopted, meaning that the two objectives are combined with a parameter $\alpha \in [0, 1]$:
$\alpha \max u + (1 - \alpha) \max \sum_{t \in T} \sum_{p \in P} x_{tp} - \sum_{t \in T} \pi_t \cdot w_t$
The value of α thus controls the relative importance of the two objectives.

3.4 Simulation Scenario

Due to the observations of telecommunication market trends described at the beginning of this chapter, a multi-RAT wireless scenario with three

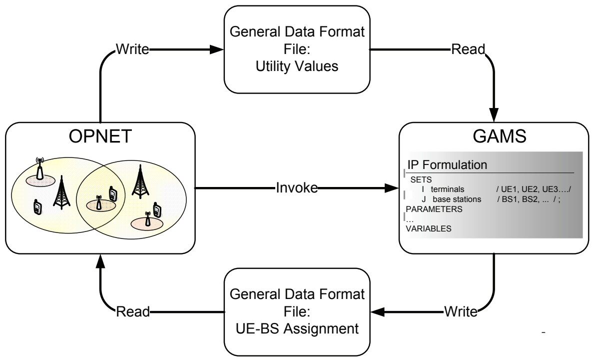


Figure 3.4: Integration of OPNET Modeler and GAMS.

RATs (EDGE, HSPA and LTE) is considered in this study. The goal is to provide the multimode UEs the best possible connection by choosing the most appropriate RAT and assigning necessary resources so as to meet their service requirements.

The test scenario is developed in OPNET Modeler [78]. Furthermore, the network simulator is interfaced with GAMS [79] which uses CPLEX [80] as an ILP solver. As depicted in Fig. 3.4 network parameters are periodically extracted from OPNET and once the input files are ready, the network simulator invokes GAMS. Further on, the simulator can access the results of optimisation and proceed with the simulation run until the next optimisation call. This approach is much different from solving an optimisation problem for a number of scenarios extracted from simulations. Since the model considers two consecutive time slots, feeding back the solution during an ongoing run directly influences the network behaviour and allows for a more accurate observation of optimisation effects. The following sections will present the network model considered in this work more in detail.

3.4.1 Network Architecture

We consider a target area covered by three RATs offering service to a number of UEs. Uniformly distributed mobile users with multimode UEs are able to connect to any of them any time. They are randomly distributed and move around the coverage area with a uniformly distributed speed. BSs provide control information over their broadcast control channels specific to each RAT. Every multimode UE is equipped with three radio interfaces, one per RAT to monitor the system information and perform periodic reporting of their Channel Quality Indicators (CQIs) towards a particular BS and RAT. This information is further forwarded to the central management entity that performs optimisation as described in the preceding section. Perfect synchronisation between the RATs and error-free transmissions of CQIs is assumed.

UEs generate call requests, as described in 3.4.3. CAC processes them periodically and assigns UEs to particular BSs and RATs using the optimisation procedure described in 3.3.3. Once a UE transits from idle to connected mode, data transfer over a data traffic channel starts. If during an ongoing call the assignment of BS/RAT changes, we assume that a seamless vertical handover occurs instantaneously. In a situation when no resources are assigned, a connection to the last chosen BS and RAT is maintained for control purposes.

3.4.2 Network Resources

For evaluation purposes one cell served by multi-RAT BS is considered. The focus is on the downlink transmissions and the resources available in the network are 7 time slots, 15 codes and 25 Physical Resource Blocks (PRBs) for EDGE, High Speed Downlink Packet Access (HSDPA) and LTE, respectively. Multimode UEs are capable to operate in all three RATs.

All the considered access technologies enable Adaptive Modulation and Coding (AMC), the UEs perform measurement of the received Signal to Noise Ratio (SNR) and map it to an appropriate Modulation and Coding Scheme (MCS). The values of SNR thresholds are adopted from [81] for EDGE and HSDPA. Mapping for LTE is based on [16] and shown as an example in Table 3.2. Transport Block Size (TBS) is determined based on the MCS and is done according to the documentation of the standards [82–84].

3.4.3 Traffic Model

According to [85] video comprises 30% of the mobile traffic traffic on laptops, tablets and smartphones. Another 30 to 40 % consists of web

Table 3.2: AMC in LTE [16]

SNR [dB]	MCS	Modulation	Coding
-6.5	MCS 1	QPSK	1/12
-4.5	MCS 2	QPSK	1/9
-2.5	MCS 3	QPSK	1/6
-0.1	MCS 4	QPSK	1/3
1.5	MCS 5	QPSK	1/2
3.5	MCS 6	QPSK	3/5
5.0	MCS 7	16QAM	1/3
7.0	MCS 8	16QAM	1/2
9.0	MCS 9	16QAM	3/5
11.0	MCS 10	64QAM	1/2
12.5	MCS 11	64QAM	1/2
15.0	MCS 12	64QAM	3/5
16.5	MCS 13	64QAM	3/4
18.0	MCS 14	64QAM	5/6
20.0	MCS 15	64QAM	11/12

browsing including social networking, e-mail and file sharing. The remaining part we allocate to Voice over IP (VoIP) services. Three types of traffic are considered in this scenario, as aforementioned. As for the VoIP traffic characteristics, 16 kbps with G.728 codec, 32 kbps with G.726 and 64 kbps with G.711 codec is modelled following [86]. Video traffic is modelled according to the specification [87] whereas Hypertext Transfer Protocol (HTTP) traffic model is adopted from [88]. Traffic models are summarized in Table 3.3.

3.4.4 Utility Function

Many proposals of the utility function definition for RAT selection purposes are available in the literature, for example [34–36, 89, 90]. These definitions take into account a number of various factors, such as UE capability, cell load, service cost or link quality among others. The utility function definition in this study is strongly related to user mobility and radio conditions measurement, which every UE performs periodically. As explained in 3.4.2 all the considered RATs use AMC, where particular

Table 3.3: Traffic Model Details

Traffic	Parameter	Characteristics
Video	Frame size [packets]	8
	Frame interarrival time [s]	Deterministic: 0.1
	Packet size [bytes]	Truncated pareto: mean 50, k=40, α=1.2
	Packet interarrival time [s]	Truncated pareto: mean 0.006, k=2.5, α=1.2
VoIP	ON time [s]	Exponential: mean 1.34
	OFF time [s]	Exponential: mean 1.67
G.728	Packet size [bytes]	60
	Packet interarrival time [s]	0.03
G.726	Packet size [bytes]	80
	Packet interarrival time [s]	0.02
G.711	Packet size [bytes]	160
	Packet interarrival time [s]	0.016
HTTP	Packet size [bytes]	Pareto: mean 81.5 α=1.1
	Packet interarrival time [s]	Normal: mean 0.0277, st.dev. 0.01
	Session size [packets]	Normal: mean 25, st.dev. 5
	Reading duration [s]	Exponential: mean 5

channel quality in terms of SNR is mapped to an MCS. Consequently, MCS translates to TBS and achievable throughput. Therefore, it is a straightforward approach to design the utility function in such a way, that it is solely dependent on throughput. For this purpose the utility function proposed in [35] is modified to the form given below.

$$U = \frac{min\{T_{net}, T_{max}\} - T_{req}}{T_{max} - T_{req}} \tag{3.2}$$

where T_{net} is the throughput offered by the network which is estimated based on the radio conditions of the UE and the number of resources to be allocated with a given MCS. T_{req} represents the throughput requested by a UE and T_{max} is the maximum throughput available for a given application. Such formulation guarantees the requested throughput with minimum number of resources, since as soon as $T_{net} > T_{max}$ the utility equals 1. Until that stage, it explores the potential of a UE to increase its utility by assigning more resources.

In the simulation run, the utility is calculated for every possible resource assignment for each UE based on reported CQI. Thus, UEs have a chance to be assigned the maximum number of resources they are capable to manage.

3.4.5 Network Model Assumptions

The proposed optimisation model is very generic and can be applied to numerous network scenarios, including multi-RAT networks, HetNets, and C-RAN. It can be also used in a scenario where traffic offloading is considered. All of the above are subject to utility function definition corresponding to the scenario. The utility function presented here could be further enhanced with other decision factors, as mentioned at the beginning of this section. It would not affect the general principle of the proposed optimisation model, though.

The network model focuses on MLB optimisation and does not consider MRO optimisation. If during an ongoing service, a change of BS/RAT assignment is observed, it is counted as a handover and assumed to occur instantaneously. Furthermore, if no resources for data transmission are assigned, the connection is maintained to the last chosen BS/RAT for control purposes. It should be noted, that the simulation network model contains simplifications required to make it computationally manageable. Due to software license restrictions and long simulation execution time, only one multi-RAT BS is considered in the network scenario. Therefore, the obtained results may differ from those that could be provided by a real multi-RAT network. However, since all the parameters are compliant and consistent throughout all the scenarios, the relative analysis is valid.

3.5 Results

Performance evaluation of the proposed optimisation model is done by means of simulation integrated with concurrent optimisation. The investigation focuses on network throughput and handover frequency reduction resulting from the proposed model as a part of the control platform of a multi-RAT network. The simulation parameters are summarized in

Table 3.4: Simulation Parameters

Parameter	Value
Number of cells	1 with 1 multi-RAT BS
Cell radius [km]	1
RATs	EDGE, HSPA, LTE
Available resources	7 time slots, 15 codes, 25 PRBs
Number of UEs	70
UE mobility model	Random Waypoint
UE max. speed [km/h]	3, 5, 10, 20, 60
Simulation duration [s]	300
Optimisation time interval [ms]	100

Table 3.4. All the simulation results are presented with 95% of confidence interval.

3.5.1 Comparison With Max SNR Scheme

Initially, the proposed RAT selection and resource allocation scheme is compared against the one based on maximum SNR, where UEs are associated with the BS/RAT that offers the best downlink radio channel conditions indicated by the highest SNR.

Optimisation allows for defining the bounds of the network performance in a particular set-up. Fig. 3.5 presents the average network throughput as a function of the maximum UE speed varied from 3 to 60 km/h. It is observed that RAT selection and resource allocation based on Max SNR provides higher network throughput than the proposed optimisation model. This is caused as the baseline model follows the best radio conditions leading to higher throughput, whereas the optimisation model allows a handover only in case of a significant utility function improvement when the gain is higher than the handover penalty.

However, while comparing the number of handovers shown in Fig. 3.6 it can be clearly seen that the scheme proposed in this work highly outperforms the classical one. Please note that to present the significant

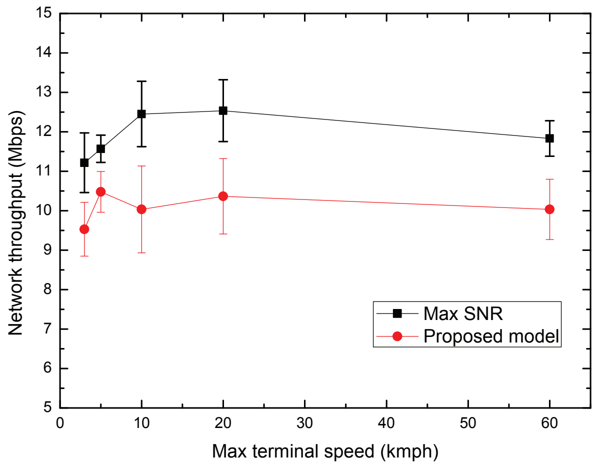


Figure 3.5: Average network throughput, α 0.5, π_t 0.5.

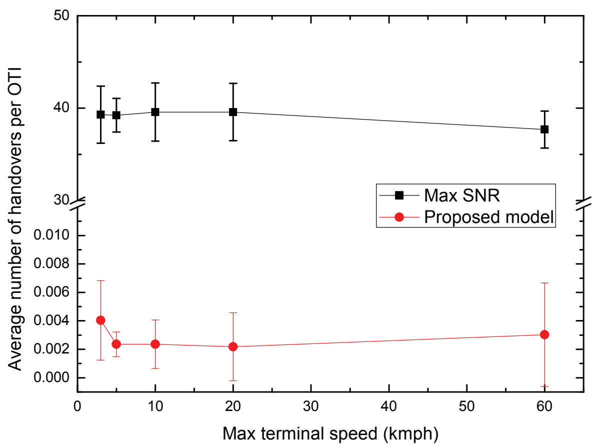


Figure 3.6: Average number of handovers, α 0.5, π_t 0.5.

difference in terms of number of handovers between the two schemes precisely, the scale of the Y axis had to be adjusted. Max SNR enforces a handover much more frequently, and on average 50% of UEs change their assignment every Optimisation Time Interval (OTI) whereas the proposed scheme aims at maintaining the connection to a particular BS and RAT as long as it satisfies the UE's demand with respect to utility

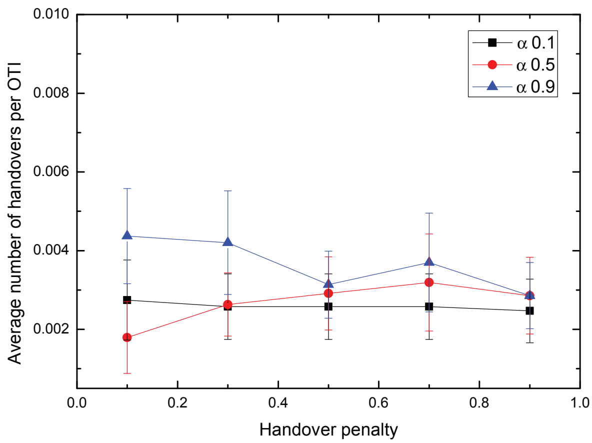


Figure 3.7: Average number of handovers as a function of α and π_t.

value. The average number of handovers per OTI is much lower and more stable assignments and handover reduction is achieved at a cost of slight throughput degradation as discussed above.

3.5.2 Optimisation Model Evaluation

This subsection provides the characteristics and analyses performance properties of the proposed optimisation model. Let us recall the final objective function, $\alpha \max u + (1-\alpha) \max \sum_{t \in T} \sum_{p \in P} x_{tp} - \sum_{t \in T} \pi_t \cdot w_t$. Minimum utility u is in the range [0,1] and the other part of the sum is upper limited by the total number of users in the system. According to our computational experience the value of α parameter does not have big influence on the network performance in terms of throughput. Fig. 3.7 shows the influence of α and π_t parameters on the number of triggered handovers. As expected, it decreases with the increase of π_t. Due to the formulation of the objective function higher values of α should enable more frequent handovers but the results show limited impact (highly overlapping confidence intervals).

On the contrary, handover penalty π_t, which can have different value depending on the RAT or a UE, has more influence on the final result. In Fig. 3.8 the lower handover penalties result in a higher network throughput. This happens because handover penalty at a low level enables more

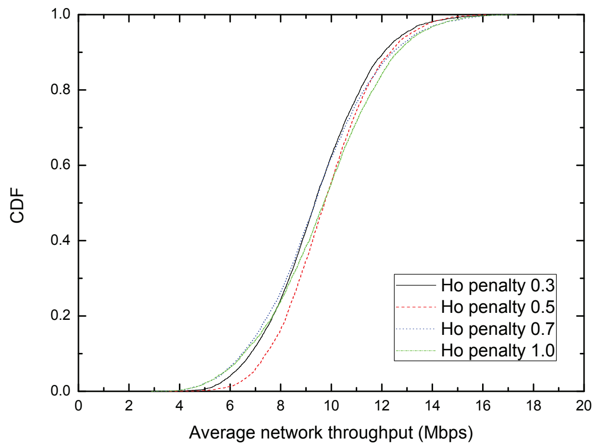


Figure 3.8: CDF of the network throughput, α 0.5, max. speed 5 km/h.

frequent assignment change. The system aims at improving the utility value and maximising minimum utility u. On the other hand, when the handover penalty is set to higher values, the assignment is changed only in case of significant utility value improvement. As a consequence, high handover penalty leads to lower network throughput but mitigates the impact of handovers and keeps the UE-BS/RAT coupling more stable.

3.6 Conclusions

This chapter has discussed the problem of RAT selection and resource allocation in multi-RAT networks. A novel optimisation model was proposed and evaluated through simulation with concurrent optimisation. The model aims at optimising double objectives: The minimum utility among all the served users and the number of connected users at the same time. Furthermore, it mitigates the one-time use characteristics in the existing solutions and considers handover as an additional decision dimension. Therefore, it takes into account two consecutive time slots and reuses the solution from the previous time slot with the goal to minimise the occurrence of a handover.

Performance of the model is evaluated using instances from the simulation of a multi-RAT network including EDGE, HSDPAand LTE. The proposed scheme was compared with the baseline which is the Max SNR. The results show that the proposed optimisation model highly outperforms the classical approach. Obtained results indicate that the handover frequency can be significantly reduced at the cost of a slight overall network throughput degradation. The model can be used as an integral part of an RRM system, as taking advantage of the technology and channel state diversity leads to overall better resource utilisation in multi-RAT networks.

The utility function used for performance evaluation was solely based on throughput. However, it can be easily enhanced with other factors such as service price or network load. These factors can be taken into account with different weights summing up to unity. Definition of the utility function affects the resource utilisation and overall network performance resulting from a particular matching, and is therefore an interesting topic itself. Furthermore, after adopting a suitable utility function the proposed optimisation model can be applied to a number of heterogeneous wireless network scenarios, including call admission control and resource allocation in HetNets, traffic offload case and C-RAN.

In the so much competitive telecommunication market, operators may want to take into account their benefits from providing a service to a UE in a given way and this can be also reflected in the utility function. Regardless the utility definition the objective and the optimisation model remain unchanged. This demonstrates great flexibility of the proposed solution and shows that it can be applied to a number of different deployments and operators' business models.

Chapter 4

Dual Connectivity in Heterogeneous Networks

This chapter directs the attention towards HetNets, where a macrocell is overlaid by small cells, e.g., metro-, pico- and femtocells. The new dual connectivity architecture with C-plane and U-plane split is described. A feasibility study focuses on a soft-pilot assignment problem which is solved using a proposed ILP model and a number of heuristics. Furthermore, discussion of benefits in terms of mobility management and energy efficiency is provided.

After introductory motivation, a new HetNet architecture is presented in detail in 4.2. Ways of implementation are shown and an example realisation proposal is given in 4.3. The feasibility study is covered in Section 4.4, followed by the discussion of applicability, benefits analysis and explanation of the shortcomings of this new architecture in 4.5. The chapter conclusions are drawn in 4.6.

4.1 Introduction

Network operators face major capacity challenges in order to address consumer demands and traffic growth. Introducing small cells as the second deployment tier is the next major step in enhancing network capacity. Small cells have a number of advantages, such as further support for ubiquity and low cost of deployment. Small BS are very light in weight, which makes them easy to deploy. Since they are usually mounted below rooftops and often indoors, small cells bring capacity closer to end user. This very often results in better QoE perceived by the users, as there are less UEs in a small cell. Introduction of small cells is a paradigm shift in cellular networks towards heterogeneous deployments and the changes are already ongoing on a broad scale. It is estimated that the number of small cell BSs exceeded the number of traditional macro sites at the end of 2012 [91].

It is important to note that in order to fully exploit the potential of small cells, a number of technical challenges still need to be addressed. As highlighted in Chapter 1 major concerns are related to the interaction between the macro and the small cell tiers. This includes schemes for efficient mobility management and interference [41,46,92]. Furthermore, even though the transmission power of small cells is much lower than that of macro cells, their number is significantly higher and therefore, their consumed energy to a high extent contributes to OPEX. From an energy saving perspective, there is a high potential in reducing the transmission power or putting a small cell into sleep when the resource utilisation becomes low, as proposed in [43,44].

Industrial as well as academic communities direct their efforts towards solving the problems indicated above and one of the recent proposals that gained a lot of attention also within 3GPP include a novel HetNet architecture. In the new network design, C-plane information necessary for establishing a connection and user data may be delivered by two different nodes [47–49]. This dual connectivity concept is described in detail in the next section.

4.2 Dual Connectivity Concept

The new network architecture is based on the idea of splitting the C-plane and U-plane in such a way that the macrocell handles C-plane for both, itself and all the underlying small cells. Hence, it is referred also as Macrocell Assisted (MA) small cell architecture. The data connection is provided as usual by the macro or small cell, depending on channel quality and cell association.

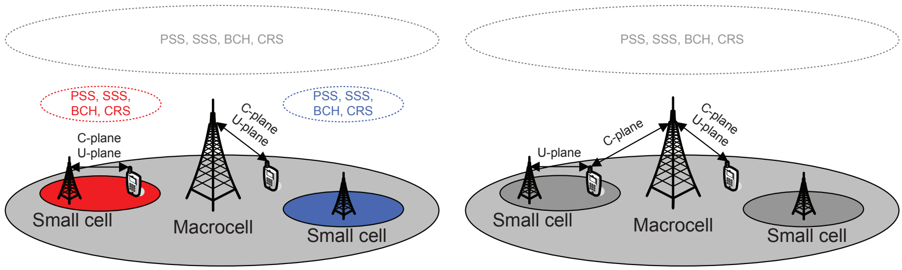


Figure 4.1: Dual connectivity in HetNets.

More specifically, C-plane is responsible for providing system information and acquisition signals through broadcast channels. Furthermore, it enables connection establishment and release, and handles mobility operations. On the other hand, U-plane provides all UE-specific data.

In LTE for example, C-plane is comprised of Primary Synchronisation Signal (PSS), Secondary Synchronisation Signal (SSS), Broadcast Channel (BCH) and Common Reference Signal (CRS). The first two signals are used by UE for synchronisation purposes and once synchronised, the UE can acquire a cell ID, which later on allows for detection of a pilot signal, here CRS, and finally decode all the system and access related information transmitted within BCH [93].

As opposite to the traditional approach, when a dual connectivity scenario is considered, only the macrocell transmits these C-plane signals. Both macrocell and small cells provide the data connection to the UEs in their vicinity, as illustrated in Fig. 4.1.

Such approach allows for energy efficiency and facilitates mobility management. First of all, because small cells take care only of the data connection and do not need to transmit acquisition signals, they can be put into sleep for a longer period of time and save more energy. Moreover, since paging messages are sent by the macrocell, this brings additional energy savings at the small cell side. Whenever needed, they can be woken up by themselves by using sniffers or by the umbrella macrocell. Benefits of separating signalling from the small cells were evaluated in [94] and it was shown that this set-up can improve energy efficiency over 4 times when compared to traditional architecture. A similar study performed in [49] reports over 30 % of energy consumption reduction.

Another clear advantage of dual connectivity architecture regards handling mobility events. In the traditional set-up, presence of small cells is a source of handover increase, many of which may be unnecessary and may result in handover failures or ping-pongs. In the new architecture, since the small cells do not transmit their C-plane and acquisition signals, they become invisible to UEs. Hence, UEs do not trigger a standard handover to a small cell and mobility is handled by the macrocell. It is the macrocell that handles the establishment and release of the Radio Resource Control (RRC) connections and signals these updates to UEs. This will significantly reduce the handover related events and signalling, and consequently improve the ratio of successful events and maintain a more stable connection.

The dual connectivity architecture provides high degree of flexibility. In [48] the authors propose to use the conventional frequency around 2 GHz for the C-plane and U-plane provided by the macrocell and high frequency bands, e.g., 3.5, 5, 10 GHz for small cells. Besides the benefits described before, this solution brings also capacity boost. Higher spectrum is advantageous for shorter range transmission of small cells due to interference suppression and provides larger bandwidths, e.g., 100 MHz to further improve system performance and deliver higher throughput. Frequency separation also facilitates interference mitigation among the cells at both tiers.

4.3 Implementation

Dual connectivity requires synchronisation between the macrocells transmitting the C-plane and all the underlying small cells providing the U-plane and this could be easily implemented within the DBS or C-RAN BS architectures discussed in Chapter 1. Centralized BB processing greatly aids cooperation between the connected nodes and can thus help in proper establishment of the RRC connections and handling mobility. However, as discussed in Chapter 2, the fronthaul has very stringent requirements in terms of throughput and delay. Moreover, since fibre connections are yet not very common worldwide, other ways of implementing this concept supporting non-ideal backhaul between macrocell and small cell tiers will need to be developed as well [95–97].

4.3.1 Soft-pilot Concept

Removing the C-plane from the small cells poses numerous challenges. Pilot signals are primarily used for cell selection and Channel State Information (CSI) estimation and in the lack of those, UEs will not be able to measure the signal strength quality of small cells. Further on, macrocell handling all the connectivity and mobility tasks will not have enough information to differentiate among all the MA small cell and identify the best serving ones for UEs.

Therefore, another signal for small cells, i.e., soft-pilot, whose duty will be similar to the removed legacy pilot, but not related to handover procedure, is required. It will play a role of small cell identifier and allow for channel state estimation by UEs. The soft-pilot used for MA small cells shall not overlap with the pilot signal used by the overlying macrocell to allow proper macrocell selection and CSI estimation. For the same reason, MA small cells should blank the resources used by the macrocell to transmit the C-plane in case of co-channel HetNet deployments. Furthermore, since from a macrocell and UE perspective the soft-pilot is the only MA small cell differentiator, it needs to be ensured that the small cell identification is unique within a given area.

4.3.2 Soft-pilot Proposal

As indicated in 4.2, the dual connectivity architecture is RAT agnostic and in this chapter an example specific case of LTE is considered. In a dual connectivity scenario where the C-plane including CRS pilot is not transmitted by the small cells, we propose the use of a new reference signal at the small cell, i.e., Channel State Information-Reference Signal (CSI-RS) and Demodulation-Reference Signal (DM-RS). These signals were introduced in LTE-A to support MIMO and CoMP transmissions [98].

CSI-RS is an antenna-port specific signal used by the UE to estimate the CSI feedback towards different antennas of a MIMO or a CoMP antenna array. It requires much less resources than legacy CRS, as it occupies fewer Resource Elements (REs) per an antenna-port and its transmission periodicity is much higher, i.e., 5-80 ms compared to 1 ms of CRS. Being antenna-specific it can also serve as a soft-pilot in the dual connectivity architecture. We propose that a UE will use legacy

CRS to identify and measure the signal quality of macrocells and a set of CSI-RSs towards MA small cells. It needs to be noted, however, that the number of standardized CSI-RS is limited to 40 which calls for an efficient planning and reuse scheme.

DM-RS is a pilot signal used only for coherent demodulation purposes. It is therefore UE-specific and inserted only when there is data scheduled for a UE. This approach reduces signalling overhead and energy consumption used for legacy pilot transmission.

To sum up, implementing dual connectivity scheme requires designing or designating a small cell specific signal to serve as a soft-pilot for identification and channel state estimation purposes. In order to realize this we propose to use reference signals introduced in LTE-A to support MIMO/CoMP operation at the small cells, namely CSI-RS and DM-RS. In this configuration UEs can perceive MA small cells as antennas of a MIMO array. As opposite to the implementation presented at the beginning of this section, the proposed set up does not require an ideal-backhaul allowing for a distributed network framework deployment.

4.4 Feasibility Study

Determining the soft-pilot together with its proper assignment to MA small cells is a key problem to be solved when implementing the dual connectivity framework. Correct assignment should not lead to collision or confusion issues, as shown in Fig. 4.2, such that UEs and the overlying macrocell can clearly differentiate among MA small cells to take measurements necessary for cell (re)selection and channel dependent scheduling. In the figure, different colours correspond to different soft-pilot signals. Here CSI-RS is used for the feasibility study but it needs to be remembered, that any properly designed signal can play this role.

A collision occurs if at least two neighbouring MA small cells use the same signal as soft-pilot, leading to poor cell identification and channel estimation by UEs in their vicinity. From the umbrella macrocell perspective, CSI-RSs are the identifiers of the underlying MA small cells, and thus when several of them reuse the same CSI-RS, the macrocell may not be able to differentiate among MA small cells, which results in a confusion. As a consequence, control mechanisms such as RRC man-

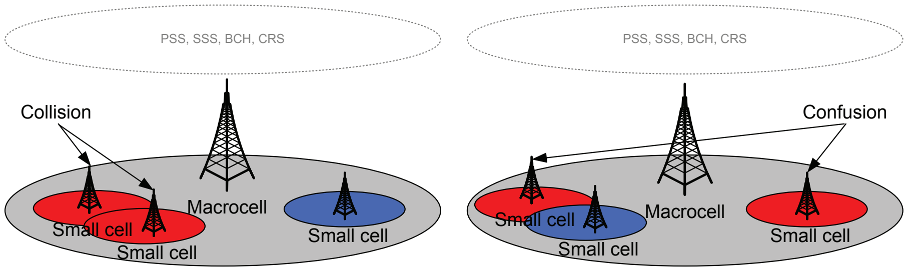
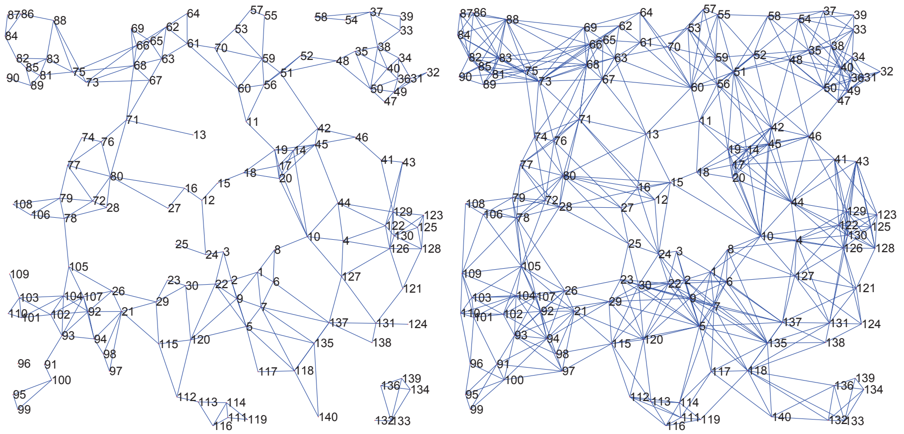


Figure 4.2: Collision and confusion example.

agement may be wrongly performed leading to disruption of the data service.

In LTE-Advanced the number of CSI-RSs is limited to 40, which calls for an efficient reuse of these signals such that above problems are mitigated. In the first step towards collision and confusion resolution, a degree of collision between MA small cells needs to be defined. Here, it is assumed that MA small cell i collides with MA small cell j if at least one of the UEs u of MA small cell i perceives the difference of the signals from the two MA small cells $p_{ij} = |p_{ui} - p_{uj}|$ within a predefined collision threshold T [99]. A collision between two MA small cells is then defined as a binary variable a_{ij} as follows $\exists u \in UEs : p_{ij} \leq T \implies a_{ij}{=}1$. Due to UEs distribution and shadow fading, results of such evaluation may not be identical for the two considered MA small cells, i.e., $a_{ij} \neq a_{ji}$. To explicitly define collision, a_{ij} is set to $a_{ij} = a_{ji} = max(a_{ij}, a_{ji})$, thus making the collision matrix symmetric and equivalent to an adjacency matrix.

Having determined the cell collision, the network can be represented as an undirected graph $G = (V, E)$ with the V and E sets defined as follows: $V = \{1, 2, ..., N\}$ is a set of vertices representing the MA small cells, and $E = \{(i, j) : i, j \in V : p_{ij} \leq T\}$ is a set of edges given as in the collision matrix. Example network graphs for $T = 9dB$ and $T = 18dB$ are depicted in Fig. 4.3. The problem of optimal CSI-RS assignment can be now solved as a graph vertex colouring problem, i.e., every vertex is assigned a colour such that no two vertices sharing an edge receive the same one, and the objective is to minimise the number of used colours [100].



(a) $T = 9$ dB (b) $T = 18$ dB

Figure 4.3: Example network graphs.

Assigning CSI-RSs according to a solution obtained by solving a corresponding graph colouring problem prevents CSI-RS collision. However, confusion resolution requires additional constraints, such that no two MA small cells under the same umbrella macrocell can receive the same CSI-RS. Depending on the number of MA small cells within the umbrella macrocell, compared to the collision free assignment, this collision and confusion free assignment may require more CSI-RSs in order to be satisfied. In the following subsections, this problem is solved using ILP and heuristic approaches.

4.4.1 ILP Formulation

The ILP formulation used to model and solve the problem of optimal soft-pilot assignment is based on [100] and its notation is given in Table 4.1. The form of the objective function allows finding optimal collision and confusion free assignments as well as exploring scenarios where confusion is allowed. If the number of available soft-pilots $|K|$ is large enough, collision and confusion free assignments are achievable. Lowering this upper bound results in confusions and its influence on the cell (re)selection can be evaluated as

Table 4.1: Notation

Parameters	Definition
Graph	
$i \in V$	set of MA small cells
$\{i, j\} \in E$	set of coupled MA small cells
$k \in K$	set of soft-pilots
$m \in M$	set of macrocells
r_i	average number of cell (re)selections to small cell i
l_{im}	$= \begin{cases} 1, & \text{if MA small cell } i \text{ is under macrocell } m \\ 0, & \text{otherwise} \end{cases}$
Decision Variables	
x_{ik}	$= \begin{cases} 1, & \text{if MA small cell } i \text{ is assigned soft-pilot } k \\ 0, & \text{otherwise} \end{cases}$
w_k	$= \begin{cases} 1, & \text{if soft-pilot } k \text{ is used} \\ 0, & \text{otherwise} \end{cases}$
y_{ijk}	$= \begin{cases} 1, & \text{if MA small cells } i \text{ and } j \text{ cause confusion using soft-pilot } k \\ 0, & \text{otherwise} \end{cases}$
z_i	$= \begin{cases} 1, & \text{if MA small cells } i \text{ is a source of confusion} \\ 0, & \text{otherwise} \end{cases}$

$$\min \sum_{k} w_k + \sum_{i \in V} z_i \cdot r_i \tag{4.1a}$$

subject to:

$$\sum_{k \in K} x_{ik} = 1, i \in V \tag{4.1b}$$

$$x_{ik} + x_{jk} \leq w_k, \{i, j\} \in E, k \in K \tag{4.1c}$$

$$x_{ik} \cdot l_{im} + x_{jk} \cdot l_{jm} \leq 1 + y_{ijk}, i \neq j \in V, k \in K, m \in M \tag{4.1d}$$

$$x_{ik} \geq y_{ijk}, i, j \in V, k \in K \tag{4.1e}$$

$$x_{jk} \geq y_{ijk}, i, j \in V, k \in K \tag{4.1f}$$

$$z_i \geq y_{ijk}, i, j \in V, k \in K \tag{4.1g}$$

$$z_i \leq \sum_{i \in V} \sum_{j \in V} \sum_{k \in K} y_{ijk}, i, j \in V, k \in K \tag{4.1h}$$

Constraint (4.1b) provides assignment of one soft-pilot to every MA small cell, while constraint (4.1c) ensures that coupled MA small cells do not use the same soft-pilot and mark it as used. Constraints (4.1d) to (4.1f) are related to confusion occurrence when two MA small cells under the same umbrella macrocell have the same soft-pilot. Finally, constraints (4.1g) and (4.1h) along with variables z_i mark MA small cells causing confusion.

4.4.2 Heuristic Approaches

Applying ILP solvers to the problem formulation above can provide an optimal solution. However, they usually require extensive computing power and/or long running time that grows exponentially with the instance size. Taking into account the dynamic nature of the network and its size, strategies providing acceptable solutions in a reasonable amount of time are needed. Hence, greedy heuristic approaches based on local best decision are discussed here.

Algorithm 1 Weighted Graph Colouring

Require: $G(V, E, W)$, max_c
Ensure: Colouring C of a weight C_w

$C \leftarrow 0$
$C_w \leftarrow 0$
$vlist \leftarrow sort_{desc}(V)$ ▷ Dsort or Wsort
for $i \leftarrow 1, |V|$ **do**
  $v \leftarrow vlist(i)$
  vn ▷ list of neighbours
  wn ▷ list of edge weights to neighbours
  cn ▷ list of neighbouring colours
  $free_c \leftarrow max_c - cn$
  if $free_c$ **then** ▷ colours available
    $C(v) \leftarrow \min free_c$
  else ▷ new colour needed to avoid collision
    $max_c \leftarrow max_c + 1$
    $C(v) \leftarrow max_c$
  end if
  $i \leftarrow i + 1$
end for
return C, C_w

Algorithm 2 Weighted Graph Coluoring: Macrocell Orthogonality

Require: $G(V, E, W)$, max_c
Ensure: Colouring C of a weight C_w

$C \leftarrow 0$
$C_w \leftarrow 0$
$vlist \leftarrow sort_{desc}(V)$ ▷ Dsort of Wsort
for $i \leftarrow 1, |V|$ **do**
    $v \leftarrow vlist(i)$
    vn ▷ set of neighbours
    wn ▷ set of edge weights to neighbours
    cn ▷ set of neighbouring colours
    ns ▷ set of vertices under the same macrocell as v
    ws ▷ set of edge weights to the same macrocell vertices
    cs ▷ list of colours used in the macrocell
    $free_c \leftarrow max_c - cn - cs$
    if $free_c$ **then** ▷ colours available
        $C(v) \leftarrow \min free_c$
    else ▷ reuse the colour of not connected vertex under the same macrocell
        $vn_{min} \leftarrow vn(\min ws - wn)$
        $C(v) \leftarrow C(vn_{min})$
        $C_w \leftarrow C_w + wn(vn_{min})$
    end if
    $i \leftarrow i + 1$
end for
return C, C_w

Sorting-based Heuristics

In heuristic approaches to graph colouring, the decision is taken step by step, as vertices are gradually coloured. Every node chooses the best possible solution locally, which means that it tries to reuse one of the already used colours. If that is not possible, a new colour needs to be introduced to the graph. Algorithm 1 presents the pseudo-code of weighted colouring based on sorting order. As one can notice, the order in which vertices take the decisions plays an important role and influences the final solution. Here, two strategies with different order are considered:

a) **Dsort**: Vertices sorted according to the vertex degree

b) **Wsort**: Vertices sorted according to sum of weights towards neighbouring vertices

As indicated when discussing the ILP formulation, traditional colouring solves the problem of collision, but not confusion. Algorithm 2 presents the approach to provide also macrocell orthogonality and avoid confusion. In this case, a set of available colours is determined not only based on the colours used by the adjacent vertices, but also vertices belonging to the small cells under the same macrocell. When number of colours is very much limited, the set of available colours for some vertices may be empty and thus, the colours will have to be reused. Here, it is important to reuse the colour of a vertex within the same macrocell that is not adjacent, thus causing confusion but not collision. Depending on the objective, the colour of the node with the lowest degree or the lowest number of handover triggers may be chosen. In this way, a local decision tries to minimise the effects of the colour reuse to make the confusion as harmless as possible.

Dsatur-based Heuristics

In Dsatur [101], the first vertex to be coloured is always the one with the highest degree. Later on, similarly as above, nodes are coloured according to the order of a list. Here, it is determined based on the so-called saturation degree, which is defined as the number of different colours a vertex is adjacent to. Pseudo code of Dsatur is given in Algorithm 3.

Algorithm 3 Dsatur-based Weighted Graph Colouring

Require: $G(V, E, W)$, max_c
Ensure: Colouring C of a weight C_w

$C \leftarrow 0$
$C_w \leftarrow 0$
$vlist \leftarrow sort_{desc}(V)$ ▷ vertex degree
$vlist(1) \leftarrow 1$ ▷ colour a vertex with max. degree with colour 1
while $v \in |V| : C(v) \leftarrow 0$ **do** ▷ uncoloured vertices exist
  $slist \leftarrow sort_{desc}(V)$ ▷ saturation degree
  $v \leftarrow slist(1)$
  $cn(v)$ ▷ list of neighbouring colours
  $free_c(v) \leftarrow max_c - cn(v)$ ▷ colours available
  if $free_c$ **then** ▷ colours available
    $C(v) \leftarrow \min free_c$
  else
    $infeasible$
  end if
end while
return C, C_w

An adjustment of Dsatur to provide confusion-free colouring is provided in Algorithm 4. The strategy of reusing a colour within a macrocell remains unchanged, when compared to Algorithm 2. Furthermore, the following modification is proposed:

Dsatur_hsat: Saturation is defined as the sum of cell (re)selections at all the coloured neighbours. This way, the algorithm first takes care of the vertices that could potentially cause much confusion and therefore is more sensitive towards the overall objective.

Algorithm 4 Dsatur-based Weighted Graph Coluoring: Macrocell Orthogonality

Require: $G(V, E, W)$, max_c
Ensure: Colouring C of a weight C_w

```
C ← 0
C_w ← 0
vlist ← sort_desc(V)                          ▷ vertex degree
vlist(1) ← 1                                  ▷ colour a vertex with max. degree with colour 1
while v ∈ |V| : C(v) ← 0 do                   ▷ uncoloured vertices exist
    slist ← sort_desc(V)                      ▷ saturation degree: classic or hsat
    v ← slist(1)
    cn                                        ▷ list of neighbouring colours of v
    hn                                        ▷ set of handover triggers to neighbouring vertices
    ns                                        ▷ set of vertices under the macrocell v belongs to
    ws                                        ▷ set of edge weights to other vertices under the macrocell
    cs                                        ▷ list of colours used under the macrocell
    hs                                        ▷ set of handover triggers to other macrocell vertices
    free_c ← max_c − cn − cs                  ▷ colours available for v
    if free_c then                            ▷ colours available
        C(v) ← min free_c
    else                                      ▷ classic: reuse of the colour of not connected vertex under a macrocell
        vn_min ← vn(min ws − wn)
        OR                                    ▷ hsat: choose the vertex with lowest number of handover triggers
        vn_min ← vn(min hs − hn)
        C(v) ← C(vn_min)
        C_w ← C_w + wn(vn_min)
    end if
end while
return C, C_w
```

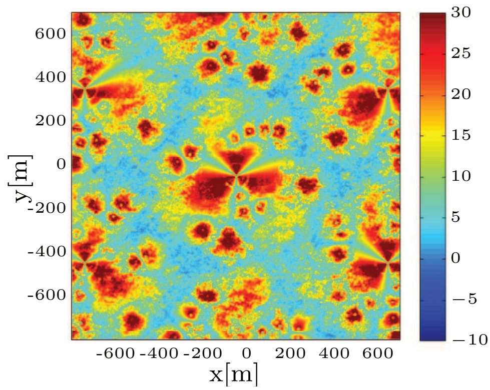


Figure 4.4: Wideband SINR [dB].

4.4.3 Simulation and Numerical Results

System-level simulations were performed to investigate both the feasibility of the proposed network architecture in terms of available CSI-RS and the performance of the assignment algorithm including corresponding collision and confusion.

The simulated scenario was downtown Dublin, Ireland, presented in [102]. Fig. 4.4 together with Table 4.2 show the simulation scenario and parameters, respectively. Macro BSs sectors and pico BSs were equipped with one antenna each, whereas UEs used two antennas. Handover statistics were collected over 10 simulation runs with independent shadow fading channel realisations. During each simulation run, 10 uniformly distributed random drops of pico eNodeBs and UEs locations were performed, and within each random drop, 100 mobile UEs moving at 30 km/h for 2 km each were deployed. Path loss and shadowing were modelled according to Table 4.2 and implementation details are given in [102]. Multi-path fading was modelled using Rayleigh fading and the Typical Urban model. Furthermore, handovers were triggered based on Reference Signal Received Power (RSRP) measurements according to [92], and CRSs were 3 dB power boosted compared to other resource elements.

Table 4.2: Simulation Parameters

Parameters	Value
Scenario	
Macro BS placement	7 eNodeBs (3 sectors each), 800 m ISD
Pico BS placement	1,2,4 or 10 pico eNodeBs per eNodeB sector
Scenario size	1500 m $\times$ 1500 m, around central macrocell
Scenario resolution	2 m
Transmit power	$P_{\mathrm{tx},n} = 21.6\,\mathrm{W}$ (macro), 1 W (picos)
Noise density	$-174\,\mathrm{dBm/Hz}$
UEs	
UE density	100 mobile UEs moving at 30 km/h for 2 km each
Channel	
Carrier frequency	2000 MHz
Bandwidth	5 MHz (1 LTE carrier of 25 RBs)
NLOS path-loss	$G_{\mathrm{Pn}} = -21.5 - 39\log_{10}(d)$ (macro) [103] $G_{\mathrm{Pn}} = -30.5 - 36.7\log_{10}(d)$ (pico) [103]
LOS path-loss	$G_{\mathrm{Pl}} = -34.02 - 22\log_{10}(d)$ [103]
Shadow fading (SF)	6 dB std dev. [104]
SF correlation	$R = \mathrm{e}^{-1/20d}$, 50% inter-site
Environment loss	$G_{\mathrm{E},n} = -20$ dB if indoor, 0 dB if outdoor
Antenna	
Height	25 m (macro), 10 m (pico)
Maximum gain	$G_{\mathrm{max}} = 15.5$ dBi (macro), 7.06 dBi (pico)
H. halfpow. beamwidth	$\alpha = 65°$ (macro), omni (pico)
V. halfpow. beamwidth	$\beta = 11.5°$ (macro)
Front-to-back ratio	$\kappa = 30$ dB (macro)
Downtilt	$\delta_1 = 8.47°$ (macro)
Handover parameters	
Time-to-trigger	160 ms
Hysteresis	2 dB
L3 filter reporting interval	200 ms
L3 forgetting factor	1/4
Preparation + Execution time	90 ms

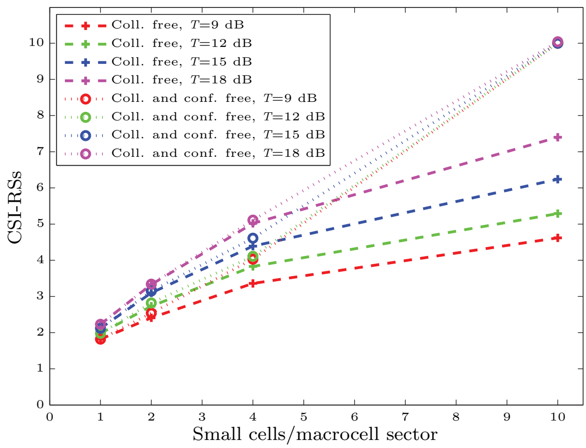


Figure 4.5: Mean optimal CSI-RS number- collision and confusion free operation.

Optimal Assignment

Using the formulation in Section 4.4.1, the ILP problem of the assignment of CSI-RSs to MA small cells in the deployments described above is solved using ILOG CPLEX [80]. Fig. 4.5 shows the relationship between the number of required CSI-RSs and the MA small cell density. For the considered scenarios, an important result is that 40 CSI-RSs as standardised by the 3GPP is sufficient to provide collision and confusion free operation. Indeed, 10 CSI-RSs are in this case enough, which leaves room for using the remaining CSI-RSs for MIMO/CoMP operations. Moreover, one can see that with the increase of the graph connectivity, which is influenced by the higher MA small cell density and threshold T, the number of required CSI-RSs for collision and confusion resolution increases. When comparing the basic colouring ensuring collision free assignment with the one preventing both collision and confusion, it is also observed that for lower MA small cell densities the number of CSI-RSs is highly driven by collision avoidance, while in denser deployments the increase of required CSI-RSs is caused by confusion resolution.

Minimising the number of used CSI-RSs, apart from reducing pilot pollution, allows UEs to perform cell search in a much faster and energy efficient manner, saving battery life. Thus, we also analyse the effect of a reduced number of CSI-RS on mobility performance in terms of

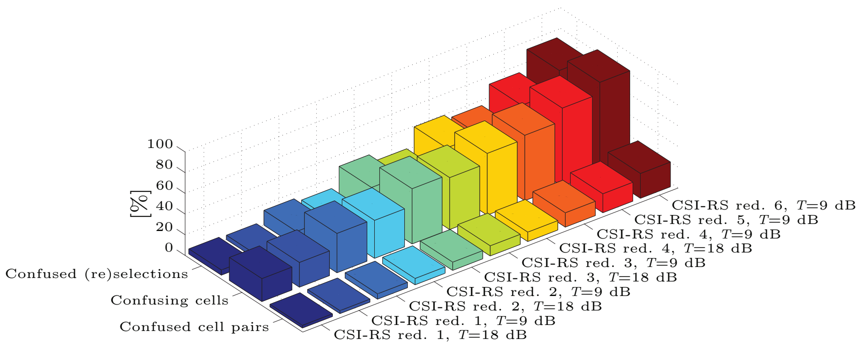


Figure 4.6: Impact of decreased number of CSI-RS on the number of confusions.

confused cell (re)selections (i.e., RRC updates towards the wrong MA small cells) when compared to the optimal assignment above. It is observed that on average the maximum allowed CSI-RS reduction, such that a collision free assignment is guaranteed, is 4 CSI-RSs and 6 CSI-RSs for collision thresholds $T = 18\,\text{dB}$ and $T = 9\,\text{dB}$, respectively, as shown in Fig. 4.5. As a result, one can conclude that there is room for CSI-RS reduction, but it significantly increases the number of confusions. For the scenarios with 10 MA small cells per macrocell sector and collision thresholds $T = 18\,\text{dB}$ and $T = 9\,\text{dB}$, Fig. 4.6 shows the percentage of confused MA small cell (re)selections averaged over an hour, the percentage of MA small cells causing confusion and the percentage of confused cell pairs when gradually reducing the number of allocated CSI-RSs until a collision free assignment is guaranteed. When reducing the available number of CSI-RSs by more than 2, we observe that more than half of the MA small cells become sources of confusion, which results in over 20% of confused cell (re)selections or higher.

Heuristics Results

The three heuristics described above, Dsort, Wsort and Dsatur are used to perform the soft-pilot assignment in all the network scenarios considered previously. Fig. 4.7 shows the number of soft-pilots required to provide collision as well as collision and confusion free operation for a number of different deployments.

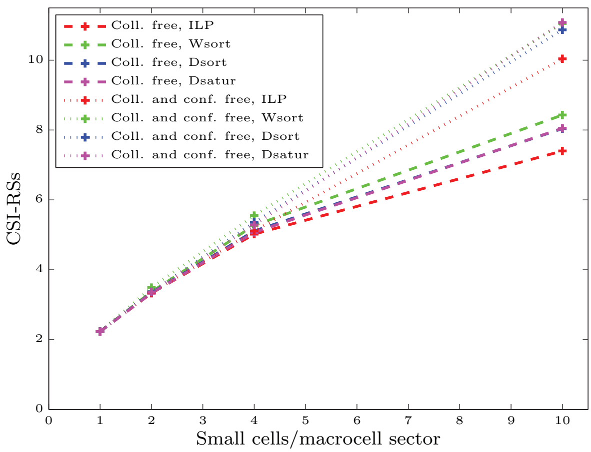


Figure 4.7: Heuristics: Collision and confusion free assignment $T = 18\,\text{dB}$.

In the case of low MA small cell density, the assignment determined by heuristic approaches is comparable to the optimal one. However, for very dense networks, more than every second solution found by heuristics require one soft-pilot more (mean number of required colours is higher by over 5%) when compared to optimal assignment. One can also notice bigger difference in heuristic performance in case of collision free assignment, where Wsort is clearly worse than the other two approaches. For collision and confusion resolution all the heuristic algorithms yield similar results.

Reducing the number of necessary soft-pilots may be of high importance. Since the objective function of the ILP formulation aims at minimisation of the confused cell (re)selections, in this study, all the heuristic algorithms allow reuse a colour of the vertex with the lowest number of cell (re)selection triggers.

As presented in Fig. 4.5, networks with 10 MA small cells per macrocell sector require 10 CSI-RSs to provide collision and confusion free operation. Therefore, in order to evaluate the heuristics, the assignment will be performed with 10 and 9 soft-pilot signals focusing on the performance metrics related to confusion. For clarity, only thresholds of $T = 9\,\text{dB}$, and $T = 18\,\text{dB}$ are considered in Fig. 4.8 that depicts the percentage of cells causing confusion, confused cell pairs and result-

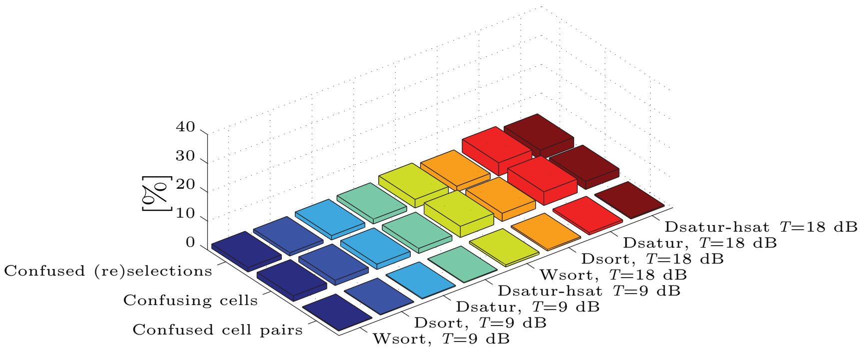


Figure 4.8: Heuristics: Number of confusions with 10 soft-pilots.

ing confused cell (re)selections averaged over an hour for four different heuristics. With the 10 soft-pilots ensuring collision and confusion free assignment by ILP, all the heuristics cause confusion. For both thresholds, the lowest percentage of confused (re)selections are provided by Dsort, at the level of 1% and 2% for $T = 9\,\text{dB}$, and $T = 18\,\text{dB}$, respectively. Better performance of the newly introduced Dsatur_hsat when compared to regular Dsatur is also observable.

Fig. 4.9 shows the results with further reduction of available CSI-RS to 9. The trends are as above with Dsort offering the lowest percentage of confused cell (re)selections but the differences among various heuristics are much larger. The performance can be compared with the CSI-RS reduction of 1 shown in Fig. 4.5. Even though we observe lower number of confusing cells in heuristic based approaches, the amount of confused cell (re)selections is approximately 2.5 times higher when compared with the optimal solution.

4.5 Architecture Benefits Evaluation

There are two main benefits resulting from this new HetNet architecture.

4.5.1 Mobility Management

In the dual connectivity framework, it is the macrocell that handles all mobility related management for itself and on behalf of all the underly-

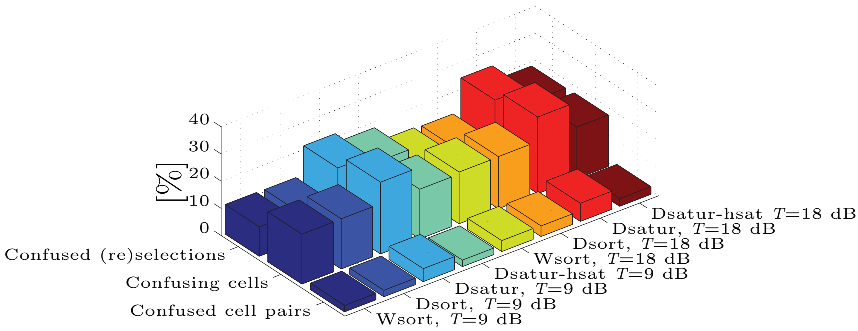


Figure 4.9: Heuristics: Number of confusions with 9 soft-pilots.

ing MA small cells. The macrocell is responsible for establishment and release of RRC connections and signalling these updates to UEs. In this way, the risk of handover failure due to wrong RRC updates is mitigated. Therefore, cell (re)selections that take place under the same macrocell umbrella can yield potential gains. In detail, this concerns the following types of (re)selections:

a) from a macrocell to an underlying small cell,

b) from a small cell to an overlying macrocell,

c) from a small cell to a small cell under the same macrocell.

In order to evaluate the potential benefits in the area of mobility management, these three types of handovers are calculated in terms of number of events per UE per hour [104] for scenarios with 10 MA small cells per macrocell and $T = 18\,\text{dB}$. The obtained results are presented in Fig. 4.10.

One can notice that the number of the cell handovers between the macrocell and underlying MA small cells is nearly the same in both directions which can be explained by the mobility model properties. Even though in this scenario handover failures were not simulated, it can be expected that in the dual connectivity architecture, these values remain very similar because macrocell controls the connectivity of UEs through a more stable and better quality connection than could be offered by

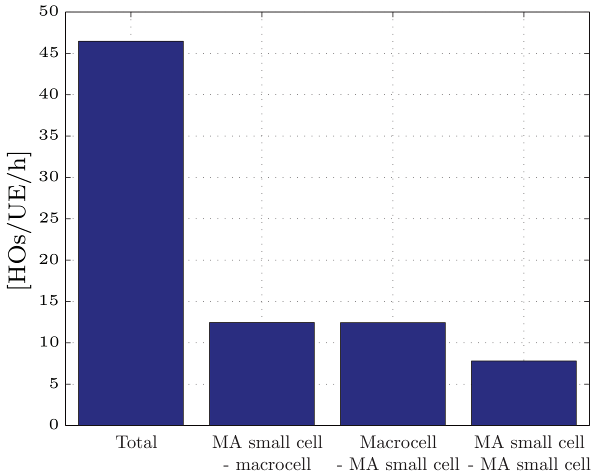


Figure 4.10: Number of handovers/UE/h. 10 MA small cells per macrocell, $T = 18$ dB.

small cells. Therefore, the risk of a RLF failure is much lower and consequently, the number of successful mobility operations is presumed to be much higher. In contrast, in the traditional architecture multiple RLFs would cause increase of additional cell reselection triggers for one of the directions depending on the network settings such as small cell range expansion bias or mobility related parameters. Another important observation is that in total, the number of three types of cell (re)selections bringing potential benefits accounts for over 70 %. For all those, the risk of a Handover (HO) failure can be minimised in the dual connectivity architecture.

4.5.2 Energy Efficiency

Dual connectivity architecture can also contribute to the reduction of energy consumption in mobile networks. The benefits could be observed both, at the network and UE side. Small cells need to transmit soft-pilots for identification purposes and to enable CQI measurements by the UEs. Hence, their periodicity can be lower than that of the macrocell pilot signal which results in energy savings. The difference between CSI-RS and CRS is as 5-80 ms to 1 ms, respectively. Furthermore, in the absence of UEs small cells can be put into micro sleep mode without the need of instant transmission of their soft-pilots. This could result in additional gains in terms of energy efficiency.

On the other hand, UEs can extend their battery life thanks to lower energy required for the pilot signal measurement. As discussed in 4.4.3, reducing the amount of soft-pilots in the network can make the measurement faster and more energy efficient. Furthermore, additional savings can be brought by the characteristics of the soft-pilot signal itself. Here, it is proposed to use CSI-RS that occupies 2 REs over 2 Orthogonal Frequency Division Multiplexing (OFDM) symbols instead of CRS using 8 REs over 4 OFDM symbols. Hence, in this dual connectivity architecture UEs would need to decode two times less symbols in order to perform the CQI reporting when compared to traditional small cell deployment. It needs to be noted, however, that the gains are available only when no data is scheduled for a UE. Otherwise, all the symbols are decoded. Quantitative analysis of saved energy requires a very detailed energy model of a UE including data about energy consumption while performing pilot measurements. Currently, no such detailed energy model is available and this could be perceived as a direction for future work.

If CSI-RS was to be used as a soft-pilot, further study needs to be performed. Recently, much attention within 3GPP has been dedicated towards the quality of RSRP measurement over CSI-RS. The link level simulation assumptions for such evaluation are documented in [105], where the pilot periodicity of 40 ms. is chosen. From the industrial contributions [106–108] it can be concluded that the factors improving measurement accuracy are:

a) higher SNR

b) higher pilot density

c) longer measurement period

Referring to the above factors, worse measurement quality can be expected in case for cell-edge and high-speed UEs. On the other hand, it is usually the more static UEs that use the service provided by small cells.

Ways of improving the measurement accuracy can be based on increasing the pilot density, e.g., from the evaluated 40 ms to 20 ms, and extending the measurement period, e.g., from 200 ms to 400 or even 800 ms. Currently in LTE the RSRP measurements are taken over 5 subframe samples within 200 ms. As one can notice, increasing the density of CSI-RS to e.g., 20 ms would make a UE decode exactly the same number of symbols as in the case of CRS, thus neglecting the potential gains. The pilot density can be increased not only in time but also frequency domain. Indeed, taking measurements over wider bandwidth results in significantly better results [109, 110].

Lastly, prolonging the measurement period can also improve the measurement accuracy. In this case, the system needs to account for longer measurement delays [110]. On the other hand, longer period would prevent fast moving users not connecting to small cells from taking unnecessary measurements. To properly realize that, a trade-off between the measurement period and the UE speed would need to be investigated.

4.6 Conclusions

This chapter provided a comprehensive overview of the new HetNet architecture with split C-plane and U-plane. The topic is of high interest among 3GPP and equipment vendors, as it can significantly mitigate mobility problems in HetNets. The framework is RAT-agnostic and offers scalable solution supporting dense deployments of small cells. It can thus be forecasted as the future network architecture. Before any real deployment takes place, some issues would need deeper and broader investigation, including cell association and mobility studies.

After removal of C-plane from MA small cells, a soft-pilot signal used as a cell identifier and for channel state estimation purposes needs to be designed and uniquely assigned to every small cell. Here, as an example soft-pilot CSI-RS was used, which is a reference signal newly introduced in LTE-A to facilitate MIMO operations.

Soft-pilot assignment problem was solved using ILP formulation and a number of heuristics. Feasibility of the new architecture was demonstrated by verifying that the number of necessary CSI-RSs for a variety of deployment scenarios does not exceed the amount defined by the 3GPP, while ensuring collision and confusion avoidance.

Potential gains resulting from the new HetNet architecture in terms of mobility and energy efficiency were also discussed. An important conclusion is that for a number of different deployment scenarios over 70 % of cell (re)selections are triggered under the same umbrella macrocell. Hence, dual connectivity can yield significant improvement of mobility management.

It should be underlined, that regardless whether one of the existing pilot signals will be used as a soft-pilot, e.g. CSI-RS, or a new designated signal will be proposed for the purposes described in this chapter, the challenge of providing optimal assignment, as well as ensuring sufficient pilot quality remain valid.

Chapter 5

Mobile Networks with Shared Resources

This chapter analyses mobile networks from a different perspective than before. In this work, cellular systems with shared resources are of interest and teletraffic theory is used for modelling and performance evaluation. A mobile network is modelled as a circuit switched network with direct routing and various network dimensioning strategies are considered in the numerical analysis. The results discuss the benefits of sharing and evaluate the gains in each of the case scenarios.

After a short introduction in 5.1, motivation of this work is discussed in 5.2 and an overview of related work is presented in 5.3. Section 5.4 introduces the network layout along with its equivalent direct routing model. Numerical results of three different scenarios are provided in 5.5 and finally Section 5.6 concludes this chapter.

5.1 Introduction

Rapid and dynamic evolution of mobile networks has resulted in deployments of various RATs that nowadays form a network with highly overlapping cells. This provides better coverage, and higher Quality of Experience (QoE) to users with multimode terminals, as they may alternate between RATs. This fast development of mobile networks is highly driven by ever increasing user expectations and popularity of mobile data

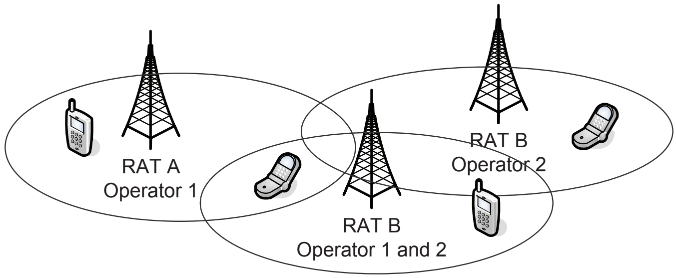


Figure 5.1: Example network with shared resources.

services. However, with the high traffic demand and flat subscriptions rates, the revenue of the operators decreases, as the cost related to network deployment, upgrades and maintenance grows at a very high speed. Therefore, operators are seeking ways to lower the CAPEX and OPEX associated with providing the telecommunication service.

One of the possible solutions to reduce the network cost is to share some of the network resources with other operators. Resource sharing facilitates higher resource utilisation, copes better with asymmetric traffic load and enables better load balancing. Sharing the BS sites is also a straightforward way to increase the network coverage. An example network with shared resources is illustrated in Fig. 5.1.

In the future, it is expected that various wireless systems will share part of the infrastructure and radio resources, cooperate, and complement each other. Such idea has already been implemented for operators that do not have their own physical network. In this case, they can lease the necessary equipment from others, thus becoming virtual operators.

Today, there are two main drivers behind resource sharing in future networks and the next section provides a detailed discussion presenting motivation for this study.

5.2 Motivation

Both challenges and deployment directions discussed below, require network resource sharing, which makes the work in this area relevant for the development of future mobile networks.

5.2.1 Spectrum Crunch

With the new broadband services and high demand for mobile traffic, future wireless systems will require much higher capacity than can be provided today. According to [111] there are three major ways of capacity enhancement, namely additional spectrum bands, higher spectral efficiency and dense deployment.

The possibility of using unlicensed spectrum around 2.4 and 5 GHz, as well as refarming 900 and 1800 MHz bands will in the future significantly increase the spectrum available for broadband data. Higher frequencies can be used for short-distance links, like in the case of small cells. It is also expected that new bands will become available after ITU-R World Radiocommunication Conference in 2016 [111].

However, new spectrum bands alone will not be sufficient to satisfy the future traffic demands. To take as much advantage of spectrum as possible, spectral efficiency should be significantly increased. Intelligent spectrum management, advanced multi-antenna techniques, such as beamforming and MIMO, together with spectrum sharing are the key enablers to achieve higher spectral efficiency.

Cognitive radio [69] is an intelligent radio capable of automatic reconfiguration. Secondary cognitive users are able to intelligently adapt their radio parameters to observed radio environment with for example the support of SDR, and to access licensed spectrum when its primary users are inactive. Dynamic Spectrum Access (DSA) can be perceived as an example of cognitive radio, which is a much broader concept [112]. Challenges and implementation directions are widely covered in [113]. Finally, one of the recent proposals considers spectrum sharing among different technologies, through for example CA between LTE and HSPA [111,114]. Here, we stress that sharing radio resources will be unavoidable in the future mobile networks. Therefore, research efforts focusing on theoretical characterisation of this kind of systems is of high importance.

5.2.2 Cloud Radio Access Network

C-RAN concept was presented briefly in Chapter 1 and it will be described more in detail here. The idea evolved from a DBS architecture where a BS server responsible for BB processing is connected over a fibre link to a number of antennas, so-called RRHs. In C-RAN multiple

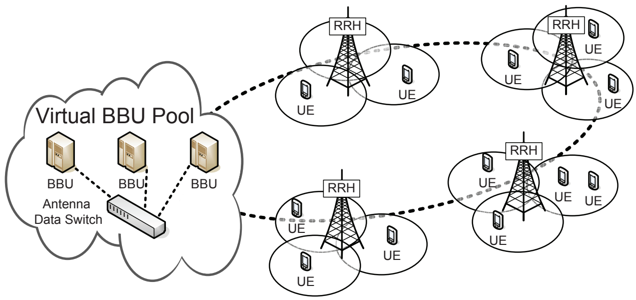


Figure 5.2: Cloud-RAN architecture.

BBUs are gathered in one central physical location to enable resource aggregation and pooling. A BBU pool serves a particular area with a number of RRHs of macro and small cells. The topology of BBU pool-RRH connections is scenario and implementation specific and C-RAN supports a wide variety of architectures, for example chain deployments for railway and other transportation networks, as well as star and ring topologies depending on the needs. There is also a flexible enhancement to interconnect RRHs to each other, so-called daisy-chaining for further coverage enhancement. An example C-RAN architecture is illustrated in Fig. 5.2 which is based on [57].

This clear separation of BBUs from antennas has multiple advantages. Together with smart antenna techniques it has the potential to significantly increase overall system capacity while keeping low energy consumption. Furthermore, thanks to BBU aggregation, the number of units can be reduced, which results in much lower cost of operation. For instance, as indicated in Fig. 5.2 only three BBUs are used to serve four BS sites, as they can be shared.

Since BBU resources are virtualised, some of the processing power can be reduced during low traffic hours, thus aiding moving the network capacity between business and residential areas. Moreover, in such a set-up locally centralized collaborative management can be employed, which leads to improved adaptability to dynamic and non-uniform traffic across all connected RRHs. It also makes network upgrades faster and easier. Finally, C-RAN supports multi-RAT operation, and in case of inter-RAT management, centralization enables joint processing in such areas as scheduling, interference coordination or traffic steering [50, 51, 57].

Cooperation and network virtualisation are becoming one of the main trends in saving OPEX and leading to better resource utilisation. C-RAN architecture facilitates sharing resource, e.g., spectrum and hardware on a BS site, among many partners. The overall benefits of such cooperation are appealing. However, it is also important to analyse the effects of sharing on the performance of collaborating partners and evaluate its influence not only on the entire system as whole, but also on individual contributors.

5.2.3 Objectives

Both examples of resource sharing introduced above concern systems with overlapping coverage. In systems with multiple services or RATs offered by one operator, the radio resources can be used separately or they can be aggregated into several groups for common use, e.g., different frequency bands for different services or entire spectrum available shared among all of them. Naturally, the second approach is more efficient and allows for a better resource utilisation. While the overall advantage of systems with shared resources is clear, its effect on services, RATs or operators needs further investigation.

In Chapter 2 the proposed resource management framework assumed that every partner manages its own resources. As the tendency moves towards network sharing, the goal of this work is to study theoretical aspects of such cooperation, perform quantitative analysis of the resource sharing influence on the network performance and evaluate its benefits for individual partners.

5.3 Related Work

Most existing works on systems with shared resources focus on access methods, but a few proposals are directed towards performance and economic effects of resource sharing. Among those, [115] discusses infrastructure sharing strategies between the 3G and beyond network operators. The users are allowed to use different networks thanks to roaming agreements. The authors investigate three different radio resource management schemes, namely complete partitioning, dynamic partitioning, and adaptive partitioning with borrowing. The authors conduct studies for two operators and analyse the cell load utilisation. Furthermore, they state that the capacity available to an operator should depend upon the payment amount, but they do not investigate this further.

The impact of femtocells on the revenue of network operators is studied in [116]. The model considers one operator that offers two types of access: strictly macrocell and hybrid macro-femtocell with separated and common resources, which are understood here as split, and common spectrum scheme. The authors estimate the effect of spectrum sharing scheme on the operator's revenue. Another approach is presented in [117], where the analysis is made for a macrocell with several femtocells, and the effect of their openness has been analysed.

Some works also focus on game theoretical approach to resource and revenue sharing in wireless heterogeneous networks. In [118], the authors address the problem of competitive pricing between a number of network providers who offer the services through multiple radio access networks. The paper proposes also a method of fair revenue sharing between the cooperative operators as a result of a coalition game. They also focused on cloud providers and model the problem as a hierarchical cooperative game [119].

A method of allocating users requesting different services to various subsystems is proposed in [120]. It takes both the number of users and available subsystems into account, and analyzes the influence of the assignment gain on the multiservice capacity. The performance of networks with overlapping cells has been explored in [121]. The authors use the network direct routing model, and in the performance analysis only cells of the equal size are considered.

In this work we focus on the dynamic partitioning case where a specific part of resources belonging to a cell is open for all other operators. We also evaluate how the degree of sharing influences the operator's performance. Various scenarios with different traffic load are investigated in terms of individual performance gains. More importantly, numerous network dimensioning strategies are evaluated, e.g., fixed blocking and improvement function, and situations when equal resource sharing leads to uneven benefits are indicated and discussed.

5.4 Network Model

To represent the problem, a wireless environment consisting of multiple cells and a set of UEs that are capable of connecting to any operator or RAT offering a service at their current location is considered. The cells overlap and share some resources among each other. Inspired by the motivation of this work, the considered network model is for example applicable to the following scenarios:

a) multiple cells offering the service through different but coexisting and cooperating RATs, like LTE, HSPA or EDGE,

b) several operators offering service over certain area and sharing the resources via C-RAN,

c) an operator offering numerous services with different coverage.

In this kind of environment it is assumed that users are free to switch between all cells/RATs/operators covering their position. A neighbouring cell may belong to the same operator as the serving one, another operator, or a different RAT. Furthermore, seamless rearrangement of calls is possible between the cells. Moreover, global intelligence of the system is considered, meaning that the knowledge about the entire network is given at any level. In case when all the channels become busy in an area, particular connections may be rearranged in order to release some of the channels. In more complex systems, higher number of handovers would be needed to move an idle channel from one area to another. Global intelligence of a system is a very important assumption, as from a theoretical point of view, systems with global intelligence have the product form which makes it possible to perform traffic modelling and analysis. Due to the restrictions on the number of calls in particular areas, the network above can be represented by an equivalent circuit switched network with direct routing, which is introduced in the following sections.

5.4.1 Direct Routing Network Model

Before the entire network model with its underlying complexity is presented, a model of a single link that the network is comprised of will be introduced first.

Single Link

Let us consider a single link with capacity of n basic bandwidth units denoted here as channels. This link is offered N traffic flows of Binomial - Poisson - Pascal (BPP) traffic. Every traffic flow j is characterized by mean value A_j and peakedness (variance/mean ratio) Z_j $(j = 1, 2, \ldots, N)$. A call of flow j requires d_j channels for the entire duration of a connection. The system is assumed to work as a fully accessible lost-calls-cleared system. This means that a call from flow j will be blocked if more than $n - d_j$ channels are busy. Without loss of generality it is further assumed that all the holding times are exponentially distributed with mean value chosen as a time unit. The model is insensitive to the holding time distribution, and each flow may furthermore have individual values of mean holding time. The considered model can be described by an N-dimensional Markovian process with state space $(i_1, i_2, \ldots, i_N)$, where i_j represents the number of connections of flow j. Therefore, the state space S can be defined as follows:

$$(i_1, i_2, \ldots, i_j, \ldots, i_N) \in S, \quad i_j \geq 0, \quad i = \sum_{j=1}^{N} i_j \, d_j \leq n \, .$$

where i denotes the total number of occupied bandwidth units. The state probability $p(i_1, i_2, \ldots, i_N)$ is equivalent to the mean proportion of time when exactly $\{i_1, i_2, \ldots, i_N\}$ connections of different types are established.

Since the system has the product form, the state probability can be expressed as:

$$p(i_1, i_2, ..., i_N) = p(i_1) \cdot p(i_2) \cdot ... \cdot p(i_N).$$

Here, $p(i_j)$ is the one-dimensional state probability of flow j which is a classical BPP loss system with n channels. In order to obtain the true state probabilities, the total probability needs to be normalized, as the global state space was truncated at state n. Due to the product form, convolution algorithm introduced in [122] can be used to perform state space aggregation. For instance, flow one and two can be aggregated into a single slow as follows:

$$p(i_{12} = i) = p(i_1) * p(i_2) \mid \{i_1 + i_2 = i\}$$
$$= \sum_{x=0}^{i} p(i_1 = x) \cdot p(i_2 = i - x), \quad i = 0, 1, \ldots, n.$$

Following the same steps, N-dimensional state space can be aggregated into a two-dimensional state space, where all the flows except flow m are aggregated into one stream. This way the detailed performance measures for flow m can be found. Finally, performance measures of all the streams can be calculated by changing the order in which the convolution operation is performed.

Network

Having introduced the single link model, let us focus now on a group of such links creating a network. A network with direct routing is then characterized by number of routes N, number of links K, and channels $d_{j,k}$ used by route R_j on link L_k. This can be represented as shown in Table 5.1.

Table 5.1: Direct Routing Network

Link	Route				Capacity
	R_1	R_2	...	R_N	
L_1	$d_{1,1}$	$d_{2,1}$	...	$d_{N,1}$	n_1
L_2	$d_{1,2}$	$d_{2,2}$	...	$d_{N,2}$	n_2
.	.	.		.	.
...	...	...		...	...
.	.	.		.	.
L_K	$d_{1,K}$	$d_{2,K}$	...	$d_{N,K}$	n_K

As discussed in the case of a single link, it is possible to truncate the state space of a reversible process without changing the relative value of the remaining states and following normalisation provides probability values of the considered states. This process is slightly more complicated in case of a network. However, also in a direct routing network, the product form between the traffic flows, that is routes, enables such operation. Here, every link corresponds to a restriction. In detail, if the state space is denoted by $(i_1, i_2, \ldots, i_N)$, where $i_j \geq 0$ now represents the number of connections for route j, then the following restriction for link k can be formulated:

$$\sum_{j=1}^{N} i_j \cdot d_{j,k} \leq n_k, \qquad k = 1, 2, \ldots, K.$$

In order to keep record of the state space restriction, the number of busy channels on each link, alternatively the number of connections of each route, needs to be known. Similarly as before, the performance measures can be found using the convolution algorithm, with the difference that in this case multidimensional vectors are used for this operation.

5.4.2 Cellular Networks

Mapping between a cellular system and the direct routing network model is done in such a way that route R_i matches area A_i and a link corresponds to a particular restriction. The number of links K becomes equal to the number of contiguous areas that can be built up from the distinguishable areas. If all N cells are partially overlapping the total number of links becomes equal to $K = 2^N - 1$, after exclusion of the empty set. The link index explicitly defines routes that use it, as all the non-empty subsets of the link's indices mark the possible routes. Thus, for example link L_{ij} will be used by the routes R_i, R_j and R_{ij}.

For performance evaluation purposes, we will consider two overlapping cells of different capabilities as depicted in Fig. 5.3. This will lower the computational complexity and provide better understanding of the problem without losing generality. The use-case scenario can be interpreted as two cells belonging to different operators, using various RATs or being served by C-RAN with joint processing, where capacity can be defined as the number processors available within the pool and demand as the number of jobs to complete by the two partners. In this work, the focus is on scenario a) introduced above as a reference. Hence, the term resources is used with relation to channels, and call blocking probability will be used as the performance metric. However, in a broader context resources can refer to spectrum, computational power or infrastructure.

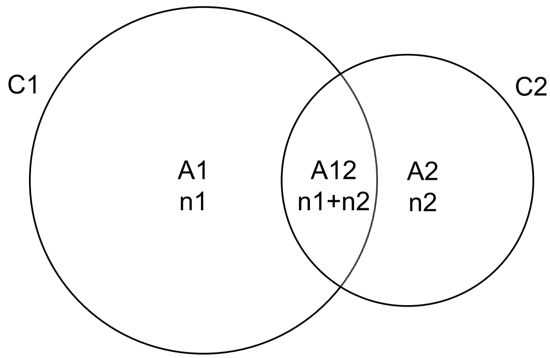


Figure 5.3: Network model.

Fig. 5.3 shows the network model considered in this study comprising of two cells $C1$ and $C2$. The cells are characterized by the number of accessible channels n_1 and n_2 in areas $A1$ and $A2$, respectively. Additionally, due to the overlap, UEs in area $A12$ have access to the services offered by both BSs and $n_{12} = n_1 + n_2$ channels. Optimal rearrangement (call packing) is assumed and therefore, users in $A12$ will experience smaller call blocking probability than those in the separate areas, as they have access to the entire pool of all the available resources.

For the cellular network model investigated in this work, a set of restrictions on the number of calls in particular areas may be formulated as:

$$0 \leq x_1 \leq n_1 \tag{5.1}$$

$$0 \leq x_2 \leq n_2 \tag{5.2}$$

$$0 \leq \quad x_1 + x_2 + x_{12} \quad \leq n_1 + n_2 \tag{5.3}$$

where x_i represents number of existing connections in area Ai. Therefore, the considered system can be transformed to a network with direct routing. Using the approach presented at the beginning of this section, the equivalent direct routing network can be obtained and Table 5.2 shows the mapping for the considered scenario.

It can be noticed that route R_1 occupies one channel on link L_1 and L_{12}, route R_2 uses channels on L_2 and L_{12}, whereas R_{12} uses only one channel on link L_{12}. Additional routes with different channel demand

Table 5.2: Direct Routing Equivalent

Link	Route			Capacity
	R_1	R_2	R_{12}	
L_1	1	0	0	n_1
L_2	0	1	0	n_2
L_{12}	1	1	1	$n_1 + n_2$

could be defined for multirate traffic. Referring to Fig. 5.3, routes are identified as follows: route R_1 corresponds to area *A1* (without the overlap), route R_2 to area *A2* (without the overlap) and finally route R_{12} represents the overlap region $A12$. Links of the example network are defined in such a way that link L_1 denotes area $A1$ corresponding to restriction (5.1), link L_2 refers to area $A2$ and restriction (5.2) whereas link L_{12} represents the entire network with a restriction defined in (5.3).

5.5 Numerical Analysis

The performance evaluation is done for three scenarios that are characterized by different traffic distributions and network dimensioning strategies. The presented model is applicable to BPP traffic, multi-rate traffic and multiple cells. To keep the case studies manageable, Poisson arrival processes, single-slot traffic, and two cells are chosen. All of the examples consider two overlapping cells of various traffic load where the users are uniformly distributed over the cells area. Due to the Poisson Arrivals See Time Averages (PASTA) property, time, call, and traffic congestion are equal and time congestion is used as a performance measure.

In the numerical experiments, the amount of traffic in the common area $A12$ can be regulated by the cell overlap percentage because of the uniform users distribution. The influence of sharing degree is then investigated in different areas of the network as indicated in Fig 5.3.

5.5.1 Proportional Traffic Load

The first case scenario considers two cells of variable traffic load that are proportional to each other. The first cell has 30 channels and offered

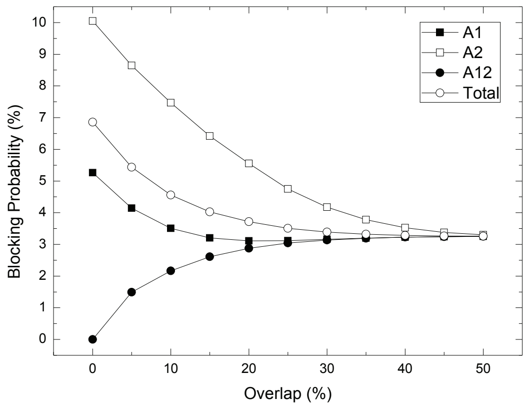


Figure 5.4: Call blocking probability as a function of cell overlap.

traffic $A1$=25 Erl. The second one is half the size with $A2$=12.5 Erl over 15 channels. Starting from the two separate cells, the overlap between the two cells is being increased gradually up to 50%, and call blocking probability is determined in all the three areas. The total blocking probability is calculated as traffic weighted average of all the areas and the obtained results are presented in Fig. 5.4.

The highest blocking is observed for separate cells (with no overlap), which is obtained by Erlang-B formula and equals 5.26% and 10.04% for the first and the second cell, respectively. With the increase of the overlap and common resources, performance of the system represented by total call blocking probability improves significantly. The overlap area $A12$ is characterized by the lowest blocking, since the users have access to all the channels of both cells. The value converges to the value of blocking for a system with total overlap which from Erlang-B formula equals to $E_{45}(37.5)$=3.25%. It can also be clearly seen that the performance of the system with only 30% of overlap is very close to the one with full accessibility.

Let us now consider a system with 20% overlap, which would result in the offered traffic of 20 Erl in area $A1$, 10 Erl in area $A2$ and 7.5 Erl in common area $A12$, where the first cell contributes with 5 Erl and the second with 2.5 Erl. We calculate the blocking in the three areas using the equivalent network with direct routing and we find it equal to 3.11% for separate area $A1$, 5.55% for $A2$ and 2.87% for common area $A12$. The weighted overall blocking is at the level of $(3.11\% \cdot 20.0 + 5.55\% \cdot 10.0 + 2.87\% \cdot 7.5)/37.5 \cdot 100\% = 3.71\%$. Noticeably, the blocking for area $A1$ is lower than for a fully accessible system and this tendency is observed for overlap higher than 15%. The lowest values are noticed for 20% and 25% of overlap and are equal to 3.11% and 3.12%, respectively. After reaching its minimum value, blocking for $A1$ steadily increases to the limiting value 3.25%. The bigger cell $C1$ clearly benefits more from this strategy, as by opening its resources for common use, it accepts only 2.5 Erl more traffic. On the other hand, cell $C2$ accepts 5 Erl more which is 40% of its own load and allows it to compete for the same n_2 channels.

In the next two test case scenarios we will investigate, whether a similar property is observed when the system is dimensioned according to fixed blocking and fixed improvement function. The goal of such dimensioning is to balance the grade of service, interpreted here as the call blocking probability, and the economic aspects of network operation.

5.5.2 Fixed Blocking

In the second scenario fixed blocking probability is considered, which is initially set at the low level of $E = 1\%$ for both cells when they are separate. The available number of channels remains the same and the offered traffic is adjusted to meet the chosen blocking rate: 20.337 Erl for the first cell and 8.108 Erl for the second cell, as given in the Table 5.3 below.

Table 5.3: Cell Parameters for Fixed Blocking $E_n(A)$=1%

Cell	C1	C2
n	30	15
A [Erl]	20.337	8.108

The experiment is performed in the same way, as before. Call blocking probability is observed as a function of the cell overlap and the results are depicted in Fig. 5.5.

Similarly to the previous scenario, the highest call blocking probability is observed for the two separate cells as set to 1%. When the overlap

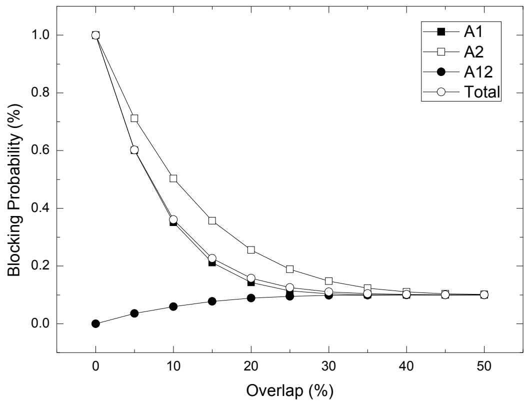


Figure 5.5: Call blocking probability as a function of cell overlap – Fixed separate blocking.

increases, blocking decreases for both areas $A1$ and $A2$ and with 30% overlap it reaches the value as for a fully accessible system which in this case from Erlang-B formula equals $E_{45}(28.45)$=0.099%. This means that thanks to channel sharing, the system performance can be significantly improved, as the total call blocking probability can be lowered by a factor of 10. Users having access to all 45 channels in overlap area $A12$ experience the lowest blocking, as their calls can be redirected to any of the cells. The system is more stable than in the previous example, as we observe constant reduction in the blocking probability and smooth convergence to the limiting value 0.099%.

5.5.3 Improvement Function Dimensioning

Finally, the third dimensioning case considers fixed improvement function, which is defined as the increase of carried traffic when the number of channels is increased by one:

$$F_n(A) = Y_{n+1} - Y_n = A\{E_n(A) - E_{n+1}(A)\}.$$

By definition $0 \leq F_n(A) \leq 1$ since a single channel can carry at most one Erlang. Setting the improvement function to a fixed value means that adding a channel to a channel group will increase the carried traffic

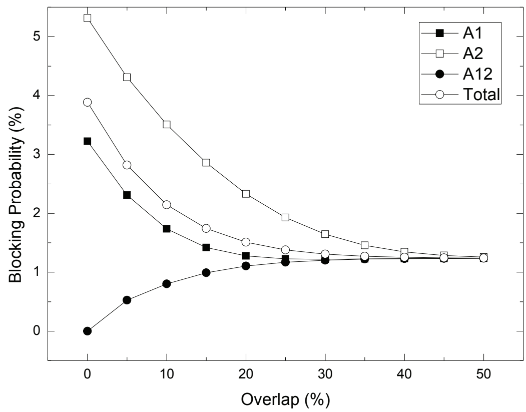


Figure 5.6: Call blocking probability as a function of cell overlap – Fixed separate improvement function.

by the same amount for all the channel groups. Here, a channel group is equivalent to a separate cell.

In this scenario improvement function is set to $F_n(A) = 0.2$ for both separate cells. The number of channels remains the same as before and offered traffic is adjusted, such that it becomes 23.284 Erl for cell $C1$ and 10.767 Erl for the second cell, as presented in Table 5.4.

Table 5.4: Cell Parameters for Fixed Improvement Function $F_n(A)$=0.2

Cell	C1	C2
n	30	15
A [Erl]	23.284	10.767
$E_n(A)$ [%]	3.225	5.314

The effect of fixed improvement function dimensioning is presented in Fig. 5.6. The figure shows that the total call blocking probability reaches lower values for higher overlap degree. We also observe similar property as in the first scenario, since blocking probability steadily decreases for area $A2$ and increases for overlap area $A12$. However, in the case of separate area $A1$, it decreases reaching its minimum value of 1.22% for 30% overlap and increases again with higher overlap converging to the

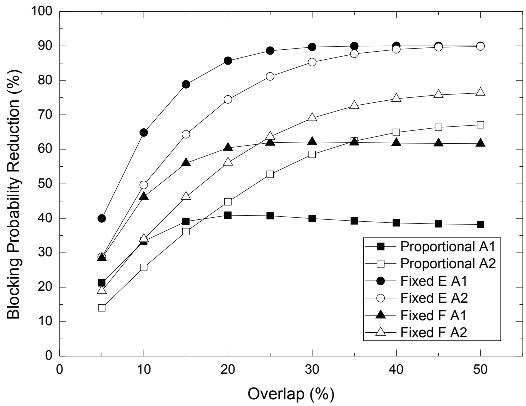


Figure 5.7: Call blocking probability reduction as a function of cell overlap.

value of blocking from Erlang-B formula- 1.24% for this scenario. It can be clearly seen that the bigger cell benefits more from the sharing resources, as in particular conditions the blocking probability drops below the value for a fully accessible system.

5.5.4 Performance Comparison

This subsection compares the results obtained in the three scenarios analysed above. For this purpose, call blocking probability reduction is introduced as a measure to perform comparative analysis. It is defined as the percentage of call blocking probability drop with regard to a scenario without resource sharing. The results are depicted in Fig.5.7.

The most fair and beneficial sharing is observed for the scenario with fixed initial blocking probability. Here, with only 30% of overlap, the blocking probability in separate areas is reduced by nearly 90% whereas for the other two analysed scenarios the reduction was possible in the range between 40% and 70%. Furthermore, we notice a general tendency of greater blocking reduction for bigger area $A1$ when compared to $A2$. For the scenario with proportional offered traffic dimensioned according to improvement function, this is true for the overlap lower than 25%. When higher resource sharing degree is considered, bigger area $A1$ reaches call blocking probability values close to those obtained from Erlang-B formula for a fully accessible system, and therefore no more improvement is observed. In this case, blocking in smaller area $A2$ is further reduced and this cell can still benefit from resource sharing. In such cases both partners would need to carefully choose the pricing policies for the use of their resources as well as the offered service. Setting service prices and developing revenue sharing schemes for the presented scenarios is another interesting and important topic in this context, but out of the scope of this work.

5.6 Conclusions

This chapter has discussed mobile networks with shared resources and presented examples motivating research in this area. As sharing resources brings multiple advantages in terms of higher overall network resource utilisation and better coverage, it is important to analyse its benefits towards individual partners in such cooperative business relationship. This chapter has presented the results of quantitative study of the influence of shared resources on the performance in such systems.

Two operators with a common pool of resources were considered along with three case scenarios with different network dimensioning strategies: proportional in terms of number of channels and traffic, with fixed blocking probability, and fixed improvement function for separate cells. A cellular network was modelled as a direct routing network and the dependence between the degree of resource sharing and call blocking probability was analysed.

It has been demonstrated that in general resource sharing is very beneficial for all the considered systems, as with only 30% of overlap i.e., partners' contribution to the common resource pool, the total blocking probability is almost the same as for a system with full accessibility. However, the results also show that cells with higher offered traffic may benefit more than their smaller collaborator as they achieve significantly lower blocking probability when sharing only a small part of their resources. The most fair benefits from sharing are observed for the case scenario with fixed initial blocking probability. In the other two analysed cases, the disproportion between the two sharing partners was much higher.

The analysis has been performed for two operators and cells but the presented study is applicable to various network scenarios including resource sharing such as multi-RAT, HetNets and C-RAN. The observations are very general and should raise the awareness of network operators about benefits of resource sharing in various network scenarios. The results presented in this chapter can be used to perform network dimensioning leading to a valuable recommendation for the operators on how to shape the sharing agreements in the best way.

Chapter 6

Conclusions and Outlook

Since the first deployment of an NMT system, mobile networks have undergone several major changes in the continuous evolution. With the advancement of wireless technologies, they have become ubiquitous offering all kinds of services from traditional telephony, through text messaging and content sharing to streamed media, and will soon support e-health, augmented reality and tactile Internet services.

This chapter summarizes the results presented in this thesis and highlights some future research directions in the area of heterogeneous mobile networks, where heterogeneity is defined three-fold as:

1. multi-RAT networks,
2. HetNets,
3. various BS architectures.

This thesis makes several contributions in the areas indicated above addressing current and future challenges in mobile networks development.

A novel generic network resource management framework aligned with the development directions of mobile networks has been proposed. It takes into account not only radio resources, as the existing models, but considers also optical and computational resources that come with the new architecture of DBS or C-RAN. Because of that, the framework is very generic and thanks to its universal character it can be applied to a network characterized by any type of heterogeneity. Furthermore, it has been shown that the framework is compliant with SON and cognitive principles, which makes it a valuable design scheme for the future management platform development. In this thesis it is discussed as a proposal and a proper implementation, followed by validation over a number of test cases should be investigated in order to fully take advantage of this framework. Improvement of the work presented in this thesis could be obtained by developing a test-scenario and a thorough evaluation of the signalling performance among the modules, paying special attention to latency.

Following this direction, a review of the available optimisation methods of serving cell selection in multi-RAT environment has been provided. Since the existing schemes perform only one-time optimization, and do not take into account handover as a decision dimension, or are characterized by heuristic properties, a novel optimisation model addressing these gaps has been proposed. Applying the $big-M$ formulation, it automatically selects users to be served and provides the optimal solution at the first attempt. Using developed simulation and optimisation models, performance evaluation has been made and the results show that the proposed scheme allows for a significant reduction of unnecessary handover operations at the cost of slightly lower throughput.

A number of future studies using the same set-up are apparent, for instance including CA between two different RATs or further evaluation of the utility function. It needs to be noted, however, that the presented study covers only MLB optimisation. In SONs MLB is highly influenced by MRO and therefore, it is desired to control not only resource utilisation through optimal RAT selection but also parameters related to the handover procedure. It would be then recommended to carry out joint optimisation in these two areas.

When addressing heterogeneity resulting from HetNet deployment, this thesis provides an evaluation of a new dual connectivity architecture based on C-plane and U-plane separation. Requirements towards a soft-pilot signal for the MA small cells have been described and an ILP model together with a set of heuristic approaches have been developed to provide collision and confusion-free assignment. It has been shown that according to 3GPP scenarios, 10 unique signals are required to ensure proper operation and thus the architecture feasibility has been demonstrated when CSI-RS is used as an example soft-pilot. Further study has revealed the potential of the dual connectivity architecture in terms of mobility management and energy efficiency.

The findings underlined above provide the following insights for future research in this direction. A more exhaustive discussion and evaluation of the energy savings than provided in the thesis would be very important. However, for that purpose a detailed energy model of a UE is required and that can be expected from the standardisation bodies in the near future. Furthermore, an additional study investigating the accuracy of CSI-RS with higher density and longer measurement period by the link level simulations would be valuable also for further design of a dedicated soft-pilot. Lastly, it would be also recommended to analyse the dual connectivity architecture from the macrocell perspective and determine signalling overhead and computational requirements related to handling the C-plane of the underlying MA small cells.

Finally, as the tendency observed in the telecommunications industry shows a clear trend towards network sharing among many providers, an analysis of the the impact of shared network resources among different operators on their network performance has been done. Using the direct routing network model the influence of the degree of resource sharing on the blocking ratio has been evaluated. The quantitative study has been performed for three different network dimensioning strategies and one of the more significant findings emerging from this study is that partners with higher number of resources benefit more from entering such collaboration. From the evaluated scenarios it can be concluded that initial network dimensioning according to fixed blocking is the most fair. The results provide an insight into sharing strategies and can be of a importance when making network deployment decisions and shaping cooperation agreements.

Specific topics in the areas outlined above have been treated separately. However, the proposed resource management framework tries to address all the aspects of mobile network heterogeneity. Given that we observe a true convergence of the wireless technologies, it would be valuable to perform an overall analysis of the entire system and investigate the trade-offs between different components, i.e., RATs, cells of different size and various BS architectures.

6.1 Towards 5G

The work presented in this thesis addresses heterogeneity in mobile networks and spans across a broad range of topics. The presented analysis, obtained results and observation of the trends in research and industry open up future work in the following directions.

6.1.1 Machine to Machine Communication

Besides network evolution, we observe also device evolution that become more and more powerful. The future wireless landscape will serve not only mobile users through such devices as smartphones, tablets or game consoles but also a tremendous number of any other devices, such as cars, smart grid terminals, health monitoring devices and household appliances that would soon require a connection to the Internet. The number of connected devices will proliferate at a very high speed. It is estimated that the Machine to Machine (M2M) traffic will increase 24-fold between 2012 and 2017 [123].

M2M communication is already today often used in fleet monitoring or vehicle tracking. Possible future usage scenarios include a wide variety of e-health applications and devices, for instance new electronic and wireless apparatus used to address the needs of elderly people suffering from diseases like Alzheimer's, or wearable heart monitors. Such sensors would enable patient monitoring and aid doctors to observe patients constantly and treat them in a better way. It will also reduce the costs of treatment, as it can be done remotely, without the need of going to a hospital.

Remote patient monitoring using a Body Area Network (BAN), where a number of wireless sensors, both on-skin and implanted, record the patient's health parameters and sends reports to a doctor, will soon become a reality and an important part of 5G paradigm. Therefore, in order to offer e-health services, 5G will need to provide high bandwidth, meet extremely high QoS requirements and implement enhanced security mechanisms. Furthermore, extended work will need to be done to efficiently manage radio resources, due to high diversity of traffic types, ranging from the reports sent periodically by the meters, to high quality medical video transmission.

6.1.2 Enhanced Local Area Access

Small cell solutions and further network densification are perceived as means to cope with the exponential traffic growth in the coming years. The additional tier of LPNs, referred also as local area access [97, 124], can significantly enhance the coverage and boost the capacity of mobile networks and it has become of a great interest in 3GPP LTE Release 12. The dual connectivity architecture discussed in this thesis is one of the key enablers to efficiently integrate both network tiers and address current research challenges related to mobility. Further directions include exploiting higher frequency bands, e.g., 3.5 GHz, and studying ideal, as well as non-ideal backhaul solutions for the small cells [97, 124, 125].

Since LTE does support interworking with both 3GPP and non-3GPP based technologies, the IEEE 802.11 standard with some of its amendments can become a great enhancement to mobile networks and help balance the traffic through efficient offload techniques. Cisco estimates that there are 800 million new WiFi devices every year [126], and an average user is surrounded by numerous hotspots that could potentially provide a service. Therefore, extensive research work on tighter interworking with WiFi can be expected. From that perspective, two amendments to IEEE 802.11 may be of particular interest.

IEEE 802.11u offers automatic authentication and handover to WiFi networks. The choice of the best available network, obtaining user credentials and finally connecting may become cumbersome. This new amendment overcomes it by automating access network discovery and selection, and supporting invisible authentication. It ensures ABC based on a set of policies and preferences defined by both, a user and network operator.

IEEE 802.11s regards Wireless Mesh Networks (WMNs), which are defined as wireless multi-hop networks formed by the static mesh routers providing distributed infrastructure for mesh clients over a full (each node communicates with all the nodes in the network) or partial mesh topology. Due to high popularity of devices equipped with WiFi, they may be nowadays used to easily extend the coverage of public wireless access, provide adaptive and flexible wireless Internet connectivity and offload mobile traffic. WMNs are easy and inexpensive to deploy, as low cost nodes with free software can be used. Furthermore, they are characterized by SON properties. This makes them an attractive alternative especially within organised communities, as the network is scalable and can grow spontaneously [127].

The coexistence of LTE and WiFi is now observable more as a co-operation rather than competition. A multimode small cell working in licensed as well as license-exempt spectrum band is available on the market. The recent proposal includes a SON based traffic steering mechanism for small cells [128]. Similarly as in JRRM [29], the delay sensitive traffic is sent over the mobile network, whereas delay tolerant data over WiFi. With the fast development of LTE and two attractive WiFi amendments, much research and standardisation efforts of 3GPP and IEEE can be expected to address the challenge of ensuring seamless interworking of these two RATs.

6.1.3 Visible Light and Millimetre Wave Communication

The spectrum used by mobile communication systems today becomes congested and alternatives are needed to meet the future capacity demands. One of the novel proposals includes using visible light bands, where Light Emitting Diodes (LEDs) can be both a source of illumination and a hotspot [129]. This technology is not mature yet but attracts more attention from the very dense small cell deployment and vehicular communication scenarios. This concept would make wireless service available in areas that nowadays have limited service, such as hospitals and aircrafts, and significantly improve indoor data coverage in general. Due to its very local character it has a great advantage when compared to radio communication, which is security and privacy, as the communication cannot be eavesdropped unless an attacker gets into visual contact with the transmitter.

There is also enormous potential in very high spectrum bands, e.g., 28 or 60 GHz that provide also wider bandwidth and can support higher data rates [130]. Millimetre waves greatly enable massive antenna solutions, thus also higher speeds. The recent extensive feasibility study of using 28 and 38 GHz frequencies for mobile communication was reported in [131].

These two areas will surely attract much attention from academic and industrial research communities in the coming years.

To conclude, 5G will be a result of standards convergence, where various technologies complement each other to reach the common goal of providing truly ubiquitous service and facilitate such services as augmented reality. Therefore, the need for an overall network resource management platform, seamless connectivity across multitude of RATs and network technologies as well as mechanisms for resource sharing will be even higher than today. Hopefully, the proposals presented in this thesis can be treated as one of the steps in this direction, and thus help to create a new wireless future.

Bibliography

[1] A. Zakrzewska, S. Ruepp, and M. S. Berger, "Towards Converged 5G Mobile Networks- Challenges and Current Trends," in *ITU-T Kaleidoscope*, 2014.

[2] A. Zakrzewska, D. López-Pérez, S. Kucera, and H. Claussen, "Dual Connectivity in LTE HetNets with Split Control- and User-Plane," in *IEEE Global Communications Conference GLOBECOM 2013, 9th Broadband Wireless Access Workshop*, 2013, pp. 390–395.

[3] A. Zakrzewska, S. Ruepp, and M. S. Berger, "RAT Selection and Resource Allocation in Heterogeneous Networks -OPNET Modeler in Optimization Studies," in *Proceedings of OPNETWORK*, 2013.

[4] E. Kisielius, A. Popovska Avramova, A. Zakrzewska, and S. Ruepp, "SON Mechanisms for Energy Efficient LTE Networks," in *Proceedings of OPNETWORK*, 2013.

[5] A. Dogadaev, A. Checko, A. Popovska Avramova, A. Zakrzewska, Y. Yan, S. Ruepp, M. S. Berger, L. Dittmann, and H. Christiansen, "Traffic Steering Framework for Mobile-Assisted Resource Management in Heterogeneous Networks," in *Ninth International ConferenceWireless and Mobile Communications, ICWMC*, 2013.

[6] A. Zakrzewska, A. Popovska Avramova, H. Christiansen, Y. Yan, A. Checko, A. Dogadaev, S. Ruepp, M. S. Berger, and L. Dittmann, "A Framework for Joint Optical-Wireless Resource Management in Multi-RAT, Heterogeneous Mobile Networks," in *IEEE International Conference on Communications 2013: IEEE ICC'13 - Workshop on Optical-Wireless Integrated Technology for Systems and Networks 2013*. IEEE, 2013, pp. 910–914.

[7] A. Zakrzewska, F. D'Andreagiovanni, S. Ruepp, and M. S. Berger, "Biobjective Optimization of Radio Access Technology Selection and Resource Allocation in Heterogeneous Wireless Networks," in *Modeling Optimization in Mobile, Ad Hoc Wireless Networks (WiOpt), 2013 11th International Symposium on*, 2013, pp. 652–658.

[8] A. Zakrzewska, S. Ruepp, and M. S. Berger, "Cell Selection Using Recursive Bipartite Matching," in *32nd IEEE International Conference on Computer Communications (INFOCOM 2013), Student Poster Session*, 2013.

[9] A. Zakrzewska, A. Popovska Avramova, S. Ruepp, M. S. Berger, and L. Dittmann, "CSMA-based SON Mechanism for Greening Heterogeneous Networks," in *32nd IEEE International Conference on Computer Communications (INFOCOM 2013), Student Poster Session*, 2013.

[10] A. Zakrzewska and V. B. Iversen, "Resource sharing in heterogeneous and Cloud Radio Access Networks," in *Ultra Modern Telecommunications and Control Systems and Workshops (ICUMT), 2012 4th International Congress on*, Oct. 2012, pp. 34–39.

[11] A. Zakrzewska, "Radio Resource Management in Heterogeneous Networks," in *Google Scholars' Retreat*, 2012.

[12] A. Zakrzewska, S. Ruepp, and M. S. Berger, "RRM Strategies in LTE and WiMAX Interworking System," in *Proc.: Second Nordic Workshop on System and Network Optimization for Wireless (SNOW)*, 2011.

[13] ——, "Modeling Multistandard Wireless Networks in OPNET," in *Proceedings of OPNETWORK*, 2011.

[14] ——, "Multistandard Radio Systems: State of the Art and Research Issues," in *Proceedings BONE-Celtic Tiger2*, 2010.

[15] Ericsson, "Traffic and Market Report, On the Pulse of the Networked Society," June 2012.

[16] J. C. Ikuno, M. Wrulich, and M. Rupp, "System Level Simulation of LTE Networks," in *Vehicular Technology Conference (VTC 2010-Spring), 2010 IEEE 71st*, 2010, pp. 1–5.

[17] "Requirements related to technical performance for IMT-Advanced radio interface(s)," ITU-R, Tech. Rep. M.2134, 2008.

[18] X. Gelabert, J. Perez-Romero, O. Sallent, and S. R. Agusti, "On the Impact of Multi-mode Terminals in Heterogeneous Wireless Access Networks," in *2nd International Symposium on Wireless Communication Systems*, 2005, pp. 39–43.

[19] W. Song, J.-M. Chung, D. Lee, C. Lim, S. Choi, and T. Yeoum, "Improvements to Seamless Vertical Handover between Mobile WiMAX and 3GPP UTRAN through the Evolved Packet Core," *Communications Magazine, IEEE*, vol. 47, no. 4, pp. 66–73, 2009.

[20] T. A. Yahiya and H. Chaouchi, "On the Integration of LTE and Mobile WiMAX Networks," in *Computer Communications and Networks (ICCCN), 2010 Proceedings of 19th International Conference on*, 2010, pp. 1–5.

[21] 3GPP, "Telecommunication management; Self-Organizing Networks (SON); Concepts and requirements," 3^{rd} Generation Partnership Project (3GPP), TS 23.401, Release 8, Feb. 2009.

[22] 3GPP, "Technical Specification Group Services and System Aspects; 3GPP System Architecture Evolution: Architecture Enhancements for non-3GPP accesses," 3^{rd} Generation Partnership Project (3GPP), TS 23.402, Release 8, Jan. 2007.

[23] J. Sachs, L. Muńoz, R. Aguero, J. Choque, G. Koudouridis, R. Karimi, L. Jorguseski, J. Gebert, F. Meago, and F. Berggren, "Future Wireless Communication based on Multi-Radio Access," in *Proceedings Wireless World Research Forum Meeting*, June 2004.

[24] R. Ferrus, O. Sallent, and R. Agusti, "Interworking in heterogeneous wireless networks: Comprehensive framework and future trends," *Wireless Communications, IEEE*, vol. 17, no. 2, pp. 22–31, 2010.

[25] Z. Sun and W. Wang, "Investigation of cooperation technologies in heterogeneous wireless networks," *Journal of Computer Systems, Networks, and Communications*, vol. 2010, pp. 3:1–3:12, Jan. 2010. [Online]. Available: http://dx.doi.org/10.1155/2010/413987

[26] K. Dimou, R. Agero, M. Bortnik, R. Karimi, G. P. Koudouridis, S. Kaminski, H. Lederer, and J. Sachs, "Generic link layer: a solution for multi-radio transmission diversity in communication networks beyond 3G," in *Vehicular Technology Conference, 2005. VTC-2005-Fall. 2005 IEEE 62nd*, vol. 3, 2005, pp. 1672–1676.

[27] IEEE, "IEEE Standard for Information Technology-Telecommunications and information exchange between systems-Local and Metropolitan networks-specific requirements-Part II: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) specifications: Amendment 9: Interworking with External Networks," IEEE, Tech. Rep. 802.11u, 2011.

[28] W. Konig, K. Nolte, T. K. Lee, R. J. Jayabal, F. Lafaye, and E. Nicollet, "Reconfigurable Base Station Processing and Resource Allocation," in *Mobile and Wireless Communications Summit, 2007. 16th IST*, 2007, pp. 1–5.

[29] J. Luo, R. Mukerjee, M. Dillinger, E. Mohyeldin, and E. Schulz, "Investigation of radio resource scheduling in WLANs coupled with 3G cellular network," *Communications Magazine, IEEE*, vol. 41, no. 6, pp. 108–115, 2003.

[30] J. Perez-Romero, O. Sallent, R. Agusti, P. Karlsson, A. Barbaresi, L. Wang, F. Casadevall, M. Dohler, H. Gonzalez, and F. Cabral-Pinto, "Common radio resource management: functional models and implementation requirements," in *Personal, Indoor and Mobile Radio Communications, 2005. PIMRC 2005. IEEE 16th International Symposium on*, vol. 3, 2005, pp. 2067–2071.

[31] F. Zhiyong, Y. Kai, J. Yang, Z. Ping, V. O. K. Li, and Z. Yongjing, "Multi-access radio resource management using multi-agent system," in *Wireless Communications and Networking Conf., 2006. WCNC 2006. IEEE*, vol. 1, 2006, pp. 63–68.

[32] E. Gustafsson and A. Jonsson, "Always best connected," *Wireless Communications, IEEE*, vol. 10, no. 1, pp. 49–55, 2003.

[33] J. Sachs and M. Olsson, "Access network discovery and selection in the evolved 3GPP multi-access system architecture," *European Transactions on Telecommunications*, vol. 21, no. 6, pp. 544–557, 2010.

[34] J. Choque, R. Agúero, and L. Muńoz, "Optimum Selection of Access Networks Within Heterogeneous Wireless Environments Based on Linear Programming Techniques," *Mobile Networks and Applications*, vol. 16, no. 4, pp. 412–423, 2011.

[35] L. Pirmez, J. C. Carvalho, Jr., F. C. Delicato, F. Protti, L. F. R. C. Carmo, P. F. Pires, and M. Pirmez, "SUTIL - Network Selection Based on Utility Function and Integer Linear Programming," *Computer Networks*, vol. 54, no. 13, pp. 2117–2136, Sep. 2010. [Online]. Available: http://dx.doi.org/10.1016/j.comnet.2010.03.007

[36] M. C. Lucas-Estañ, J. Gozalvez, and J. Sanchez-Soriano, "Integer Linear Programming Optimization of Joint RRM Policies for Heterogeneous Wireless Systems," *Comput. Netw.*, vol. 56, no. 1, pp. 112–126, Jan. 2012. [Online]. Available: http://dx.doi.org/10.1016/j.comnet.2011.08.012

[37] Cisco, "Global Mobile Data Traffic Forecast Update, 2011-2016," pp. 1–29, Feb. 2012, White Paper.

[38] A. Damnjanovic, J. Montojo, Y. Wei, T. Ji, T. Luo, M. Vajapeyam, T. Yoo, O. Song, and D. Malladi, "A Survey on 3GPP Heterogeneous Networks," *IEEE Wireless Commun. Mag.*, vol. 18, no. 3, pp. 10 –21, June 2011.

[39] J. Andrews, H. Claussen, M. Dohler, S. Rangan, and M. Reed, "Femtocells: Past, present, and future," *Selected Areas in Communications, IEEE Journal on*, vol. 30, no. 3, pp. 497–508, 2012.

[40] X. Chu, D. López-Pérez, Y. Yang, and F. Gunnarsson, *Heterogeneous Cellular Networks: Theory, Simulation and Deployment.* University Cambridge Press, 2013.

[41] D. López-Pérez, A. Valcarce, G. de la Roche, and J. Zhang, "OFDMA Femtocells: A Roadmap on Interference Avoidance," *IEEE Communications Magazine*, vol. 47, no. 9, pp. 41–48, Sept. 2009.

[42] H. Claussen, L. T. W. Ho, and L. Samuel, "Self-optimization of coverage for femtocell deployments," in *Wireless Telecommunications Symposium, 2008*, 2008, pp. 278–285.

[43] O. Blume, H. Eckhardt, S. Klein, E. Kuehn, and W. M. Wajda, "Energy savings in mobile networks based on adaptation to traffic statistics," *Bell Labs Technical Journal*, vol. 15, no. 2, pp. 77–94, 2010.

[44] J. Hoydis, M. Kobayashi, and M. Debbah, "Green Small-Cell Networks," *Vehicular Technology Magazine, IEEE*, vol. 6, no. 1, pp. 37–43, 2011.

[45] I. Ashraf, F. Boccardi, and L. Ho, "Sleep mode techniques for small cell deployments," *Communications Magazine, IEEE*, vol. 49, no. 8, pp. 72–79, 2011.

[46] D. López-Pérez, I. Guvenc, and X. Chu, "Mobility Management Challenges in 3GPP Heterogeneous Networks," *Communications Magazine, IEEE*, vol. 50, no. 12, pp. 70–78, 2012.

[47] S. Parkvall, E. Dahlman, G. Jöngren, S. Landström, and L. Lindbom, "Heterogeneous network deployments in LTE: The Soft-cell Approach," Ericsson Review, 2011.

[48] H. Ishii, Y. Kishiyama, and H. Takahashi, "A Novel Architecture for LTE-B: C-plane/ U-plane Split and Phantom Cell Concept," in *IEEE GLOBECOM*, Anaheim, USA, Dec. 2012.

[49] X. Xu, G. He, S. Zhang, Y. Chen, and S. Xu, "On Functionality Separation for Green Mobile Networks: Concept Study over LTE," *IEEE Communications Magazine*, vol. 51, no. 5, pp. 82–90, 2013.

[50] Y. Lin, L. Shao, Z. Zhu, Q. Wang, and R. K. Sabhikhi, "Wireless network cloud: architecture and system requirements," *IBM J.Res.Dev.*, vol. 54, no. 1, pp. 38–49, January 2010.

[51] China Mobile Research Institute, "C-RAN The Road Towards Green RAN," White Paper, Version 2.5, Oct. 2011.

[52] NEC Corporation, "Green radio, nec's approach towards energy-efficient radio access networks," White Paper, 2010.

[53] "Common Public Radio Interface (CPRI)." [Online]. Available: http://www.cpri.com

[54] "Open Base Station Architecture Initiative (OBSAI)." [Online]. Available: http://www.obsai.com

[55] G. Kardaras and C. Lanzani, "Advanced multimode radio for wireless & mobile broadband communication," in *European Microwave Week 2009: Science, Progress and Quality at Radiofrequencies, Conference Proceedings - 2nd European Wireless Technology Conference, EuWIT 2009*, 2009, pp. 132–135.

[56] M. Nahas, A. Saadani, J. Charles, and Z. El-Bazzal, "Base stations evolution: Toward 4G technology," in *Telecommunications (ICT), 2012 19th International Conference on*, 2012, pp. 1–6.

[57] NGMN Alliance, "Suggestions on Potential Solutions to C-RAN," White Paper, Version 4.0, 2013.

[58] H. Holma, K. Hooli, P. Kinnunen, T. Kolding, P. Marsch, and X. Wang, "Coordinated Multipoint Transmission and Reception," in *LTE-Advanced, 3GPP Solution for IMT-Advanced*, H. Holma and A. Toskala, Eds. John Wiley & Sons, 2012, pp. 184–205.

[59] J. Sachs, H. Wiemann, P. Magnusson, P. Wallentin, and J. Lundsjo, "A generic link layer in a beyond 3G multi-radio access architecture," in *Communications, Circuits and Systems, 2004. ICCAS 2004. 2004 International Conference on*, vol. 1, 2004, pp. 447–451 Vol.1.

[60] "Evolutionary Strategies for Radio Resource Management in Cellular Heterogeneous Networks (EVEREST)," http://cordis.europa.eu/projects/rcn/74605_en.html.

[61] L. M. Gavrilovska and V. M. Atanasovski, “Resource management in wireless heterogeneous networks (WHNs),” in *Telecommunication in Modern Satellite, Cable, and Broadcasting Services, 2009. TELSIKS '09. 9th Int. Conf. on*, 2009, pp. 97–106.

[62] “A cognitive radio project (ARAGORN),” http://www.ict-aragorn.eu.

[63] J. P. Vasseur, M. Pickavet and P. Demeester, *Network Recovery, Protection and Restoration of Optical, SONET-SDH, IP, and MPLS.* Morgan-Kaufmann Publishers, Elsevier, 2004.

[64] K. Dimou, M. Wang, Y. Yang, M. Kazmi, A. Larmo, J. Pettersson, W. Muller, and Y. Timner, “Handover within 3GPP LTE: Design Principles and Performance,” in *Vehicular Technology Conf. Fall (VTC 2009-Fall), 2009 IEEE 70th*, 2009.

[65] E. Dahlman, S. Parkvall, J. Sköld, and P. Beming, *3G Evolution. HSPA and LTE for Mobile Broadband.* Elsevier, 2007.

[66] J. Sachs and J. Rune, “Access Network Selection in Multi-Access Network Environment,” Patent 20 110 110 300, May, 2011.

[67] S. Hamalainen and H. Sanneck and C. Sartori, *LTE Self-Organizing Networks (SON).* John & Wiley Sons, Ltd., 2012.

[68] 3GPP, “Telecommunication management; Self-Organizing Networks (SON); Concepts and requirements,” 3^{rd} Generation Partnership Project (3GPP), TS 32.500, Feb. 2009.

[69] J. Mitola III and G. Maguire, Jr., “Cognitive radio: making software radios more personal,” *Personal Communications, IEEE*, vol. 6, no. 4, pp. 13 –18, Aug 1999.

[70] H. Wang, L. Ding, P. Wu, Z. Pan, N. Liu, and X. You, “Dynamic load balancing and throughput optimization in 3GPP LTE networks,” in *IWCMC '10 Proceedings of the 6th Int. Wireless Communications and Mobile Computing*, 2010, pp. 939–943.

[71] ETSI, "Broadband Radio Access Networks (BRAN); Very high capacity density BWA networks; System architecture, economic model and derivation of technical requirements," European Telecommunications Standards Institute, TR 101 534, March 2012.

[72] L. Giupponi, R. Agusti, J. Perez-Romero, and O. Sallent, "Joint radio resource management algorithm for multi-RAT networks," in *Global Telecommunications Conf., 2005. GLOBECOM '05. IEEE*, vol. 6, 2005, pp. 5 pp.–3855.

[73] L. A. Wolsey, *Integer programming.* Wiley, 1998.

[74] J. E. Hopcroft and R. M. Karp, "An n5/2 algorithm for maximum matchings in bipartite graphs," *SIAM J. Comput.*, 1973.

[75] H. W. Kuhn, "The Hungarian method for the assignment problem," *Naval Research Logistics Quarterly*, vol. 2, no. 1-2, pp. 83–97, 1955. [Online]. Available: http://dx.doi.org/10.1002/nav.3800020109

[76] F. D'Andreagiovanni, "Pure 0-1 Programming approaches to Wireless Network Design, Ph.D. Thesis," *4OR-Q. J. Oper. Res*, 2011.

[77] F. D'Andreagiovanni, C. Mannino, and A. Sassano, "GUB covers and power-indexed formulations for wireless network design," *Management Sci.*, 2012.

[78] "OPNET modeler, OPNET technologies, inc." [Online]. Available: http://www.opnet.com

[79] "General algebraic modeling system (GAMS)." [Online]. Available: http://www.gams.com

[80] "IBM ILOG CPLEX." [Online]. Available: http://www.ilog.com/products/cplex

[81] M. Rupp, S. Caban, C. Mehlfuehrer, and M. Wrulich, *Evaluation of HSDPA and LTE: From Testbed Measurements to System Level Performance.* John Wiley & Sons, 2011.

[82] TS 43.064, "Technical specification group GSM/EDGE radio access network; general packet radio service (gprs); overall description of

the GPRS radio interface," 3GPP Technical Report Release 9, Sep. 2009.

[83] TS 25.214, "Technical specification group radio access network; physical layer procedures (FDD)," 3GPP Technical Report Release 11, June 2011.

[84] TS 36.213, "Technical specification group radio access network; evolved universal terrestrial radio access (E-UTRA); physical layer procedures," 3GPP Technical Report Release 10, June 2011.

[85] Ericsson, "Traffic and Market Data Report, On the Pulse of the Networked Society," Nov. 2011.

[86] Cisco, "Voice over IP - per call bandwidth consumption," http://www.cisco.com/image/gif/paws/7934/bwidth_consume.pdf, online, Aug 2, 2012.

[87] TR 25.892, "Technical specification group radio access network; feasibility study for orthogonal frequency division multiplexing (OFDM) for UTRAN enhancement," 3GPP Technical Report Release 6, June 2004.

[88] H. Wang and V. B. Iversen, "Hierarchical Downlink Resource Management Framework for OFDMA Based WiMAX Systems," in *Wireless Communications and Networking Conference, 2008. WCNC 2008. IEEE*, 2008, pp. 1709–1715.

[89] J. Perez-Romero, O. Sallent, and R. Agusti, "A Novel Metric for Context-Aware RAT Selection in Wireless Multi-Access Systems," in *Communications, 2007. ICC '07. IEEE International Conference on*, 2007, pp. 5622–5627.

[90] C.-J. Chang, C.-Y. Hsieh, and Y.-H. Chen, "A Preference Value-Based Cell Selection Scheme in Heterogeneous Wireless Networks," in *Wireless Communications and Networking Conference (WCNC), 2010 IEEE*, Apr. 2010.

[91] "Small Cells Global Congress Report," 2012. [Online]. Available: http://www.thinksmallcell.com/

[92] D. López-Pérez, I. Guvenc, and X. Chu, "Mobility Enhancements for Heterogeneous Wireless Networks through Interference Coordination," in *IEEE WCNC*, Paris, France, Apr. 2012.

[93] S. Sesia, I. Toufik, and M. Baker, *LTE: The UMTS Long Term Evolution, From Theory to Practice.* John Wiley & Sons Ltd, Feb. 2009.

[94] A. Capone, I. Filippini, B. Gloss, and U. Barth, "Rethinking Cellular System Architecture for Breaking Current Energy Efficiency Limits," in *Sustainable Internet and ICT for Sustainablility (Sustain IT)*, Pisa, Italy, Oct. 2012.

[95] NTT DOCOMO, "Physical Layer Design for Dual Connectivity," St. Julian's, Malta, Feb. 2013, 3GPP Standard Contribution (R1-130409).

[96] Ericsson, "Physical Layer Aspects of Dual Connectivity," St. Julian's, Malta, Feb. 2013, 3GPP Standard Contribution (R1-130566).

[97] Y. Kishiyama, A. Benjebbour, T. Nakamura, and H. Ishii, "Future steps of LTE-A: evolution toward integration of local area and wide area systems," *Wireless Communications, IEEE*, vol. 20, no. 1, pp. 12–18, 2013.

[98] 3GPP, "Physical Channels and Modulation," TR 36.211 v 10.0.0.

[99] D. López-Pérez, X. Chu, and J. Zhang, "Dynamic Frequency Planning and Power Assignment in OFDMA Cellular Networkss," *IEEE Trans. on Commun.* , vol. 60, no. 10, pp. 2904–2914, 2012.

[100] P. Coll, J. Marenco, I. Méndez Díaz, and P. Zabala, "Facets of the Graph Coloring Polytope," *Annals of Operations Research*, vol. 116, no. 1-4, pp. 79–90, 2002.

[101] D. Brélaz, "New methods to color the vertices of a graph," *Commun. ACM*, vol. 22, no. 4, pp. 251–256, Apr. 1979. [Online]. Available: http://doi.acm.org/10.1145/359094.359101

[102] D. López-Pérez, H. Claussen, and L. Ho, "Improved Frequency Reuse Schemes with Horizontal Sector Offset for LTE," in *Personal Indoor and Mobile Radio Communications (PIMRC), 2013 IEEE 24th International Symposium on*, Sept. 2013, pp. 2159–2164.

[103] 3GPP, "Further Advancements for E-UTRA Physical Layer Aspects," TS 36.814 v 9.0.0.

[104] ——, "Mobility Enhancements in Heterogeneous Networks," TR 36.839 v 11.1.0.

[105] Ericsson, Samsung, "Link level simulation assumptions for CSI-RS RSRP measurement feasibility study ," Jeju, Korea, Mar. 2012, 3GPP Standard Contribution (R4-122202).

[106] Qualcomm Inc., "CSI-RS Based Measurements Link Level Simulation Results," Qingdao, China, Aug. 2012, 3GPP Standard Contribution (R1-123689).

[107] Qualcomm Inc., NTT DOCOCMO, "On CSI-RS-based RSRP feasibility in Rel-11," Qingdao, China, Aug. 2012, 3GPP Standard Contribution (R1-123688).

[108] 3GPP, "Draft LS response on CSI-RS based measurement for CoMP," Qingdao, China, Aug. 2012, 3GPP Standard Contribution (R4-1324224).

[109] CATT, "Link level evaluation results on CSI-RS based RSRP measurements for CoMP," Prague, Czech Republic, May 2012, 3GPP Standard Contribution (R4-122626).

[110] Huawei, "Simulation Results for CSI-RS RSRP measurement," Prague, Czech Republic, May 2012, 3GPP Standard Contribution (R4-122601).

[111] Nokia Siemens Networks, "2020: Beyond 4G Radio Evolution for the Gigabit Experience," White Paper, 2011.

[112] Q. Zhao and B. Sadler, "A Survey of Dynamic Spectrum Access," *Signal Processing Magazine, IEEE*, vol. 24, no. 3, pp. 79–89, 2007.

[113] SCF, "Perspectives on the value of shared spectrum access," Final report for the European Commission, Feb. 2012.

[114] 4G Americas, "HSPA+LTE Carrier Aggregation," http://www.4gamericas.org, June 2011.

[115] S. A. AlQahtani, A. S. Mahmoud, U. Baroudi, and A. U. Sheikh, "A Study on Network Sharing and Radio Resource Management in 3G and Beyond Mobiles Wireless Networks Supporting Heterogeneous Traffic," in *Information and Communication Technologies, 2006. ICTTA '06. 2nd*, vol. 2, 2006, pp. 2651–2656.

[116] N. Shetty, S. Parekh, and J. Walrand, "Economics of Femtocells," in *Global Telecommunications Conference, 2009. GLOBECOM 2009. IEEE*, 2009, pp. 1–6.

[117] S. Yun, Y. Yi, D.-H. Cho, and J. Mo, "Open or close: On the sharing of femtocells," in *INFOCOM, 2011 Proceedings IEEE*, 2011, pp. 116–120.

[118] D. Niyato and E. Hossain, "A game theoretic analysis of service competition and pricing in heterogeneous wireless access networks," *Wireless Communications, IEEE Transactions on*, vol. 7, no. 12, pp. 5150–5155, 2008.

[119] D. Niyato, A. V. Vasilakos, and Z. Kun, "Resource and Revenue Sharing with Coalition Formation of Cloud Providers: Game Theoretic Approach," in *Cluster, Cloud and Grid Computing (CCGrid), 2011 11th IEEE/ACM International Symposium on*, 2011, pp. 215–224.

[120] A. Furuskar and J. Zander, "Multiservice allocation for multiaccess wireless systems," *Wireless Communications, IEEE Transactions on*, vol. 4, no. 1, pp. 174–184, 2005.

[121] V. B. Iversen, V. Benetis, and P. D. Hansen, "Performance of Hierarchical Cellular Networks with Overlapping Cells," in *EuroNGI Workshop*, 2004, pp. 7–19, dBLP:conf/eurongi/2004.

[122] V. B. Iversen, "The Exact Evaluation of Multi-Service Loss Systems with Access Control," pp. 56–61, 1987.

[123] Cisco, "Global Mobile Data Traffic Forecast Update, 2012-2017," pp. 1–29, Feb. 2013, White Paper.

[124] D. Astely, E. Dahlman, G. Fodor, S. Parkvall, and J. Sachs, "LTE Release 12 and Beyond," *Communications Magazine, IEEE*, vol. 51, no. 7, 2013.

[125] T. Nakamura, S. Nagata, A. Benjebbour, Y. Kishiyama, T. Hai, S. Xiaodong, Y. Ning, and L. Nan, "Trends in small cell enhancements in LTE advanced," *Communications Magazine, IEEE*, vol. 51, no. 2, pp. 98–105, 2013.

[126] Cisco, "The Future of Hotspots: Making Wi-Fi as Secure and Easy to Use as Cellular," White Paper, 2011.

[127] I. F. Akyildiz and X. Wang, "A survey on wireless mesh networks," *Communications Magazine, IEEE*, vol. 43, no. 9, pp. S23–S30, 2005.

[128] M. Bennis, M. Simsek, A. Czylwik, W. Saad, S. Valentin, and M. Debbah, "When cellular meets WiFi in wireless small cell networks," *Communications Magazine, IEEE*, vol. 51, no. 6, pp. 44–50, 2013.

[129] H. Haas, "High-speed wireless networking using visible light," in *SPIE Newsroom*, 2013.

[130] Z. Pi and F. Khan, "A millimeter-wave massive MIMO system for next generation mobile broadband," in *Signals, Systems and Computers (ASILOMAR), 2012 Conference Record of the Forty Sixth Asilomar Conference on*, 2012, pp. 693–698.

[131] T. Rappaport, S. Sun, R. Mayzus, H. Zhao, Y. Azar, K. Wang, G. Wong, J. Schulz, M. Samimi, and F. Gutierrez, "Millimeter Wave Mobile Communications for 5G Cellular: It Will Work!" *Access, IEEE*, vol. 1, pp. 335–349, 2013.

List of Acronyms

1G	First Generation
2G	Second Generation
3G	Third Generation
3GPP	Third Generation Partnership Project
4G	Fourth Generation
5G	Fifth Generation
AAA	Authentication, Authorisation and Accounting
ABC	Always Best Connected
AMC	Adaptive Modulation and Coding
ANDSF	Access Network Discovery and Selection Function
BAN	Body Area Network
BB	Baseband
BBU	Baseband Unit
BCH	Broadcast Channel
BPP	Binomial - Poisson - Pascal
BS	Base Station

CA Carrier Aggregation

CAC Call Admission Control

CAPEX Capital Expenditure

CoMP Coordinated Multipoint

C-plane Control Plane

CPRI Common Public Radio Interface

CQI Channel Quality Indicator

C-RAN Cloud Radio Acces Network

CRS Common Reference Signal

CRRM Common Radio Resource Management

CSI Channel State Information

CSI-RS Channel State Information-Reference Signal

CSMA Carrier Sense Multiple Access

DBS Distributed Base Station

DM-RS Demodulation-Reference Signal

DSA Dynamic Spectrum Access

EDGE Enhanced GPRS

eICIC enhanced Intercell Interference Coordination

GLL Generic Link Layer

GPRS General Packet Radio Service

GSM Global System for Mobile communication

HeNB Home eNodeB

HetNet	Heterogeneous Network
HO	Handover
HSDPA	High Speed Downlink Packet Access
HSPA	High Speed Packet Access
HTTP	Hypertext Transfer Protocol
IEEE	Institute of Electrical and Electronics Engineers
ILP	Integer Linear Programming
IMT-Advanced	International Mobile Telecommunications Advanced
ITU-R	International Telecommunication Union-Radiocommunications Sector
JRRM	Joint Radio Resource Management
LED	Light Emitting Diode
LPN	Low Power Node
LTE	Long Term Evolution
LTE-A	Long Term Evolution-Advanced
M2M	Machine to Machine
MA	Macrocell Assisted
MCS	Modulation and Coding Scheme
MIMO	Multiple Input Multiple Output
MLB	Mobility Load Balancing
MRO	Mobility Robustness Optimisation
MRRM	Multi-access Radio Resource Management
NMT	Nordic Mobile Telephony

OBSAI Open Base Station Architecture Initiative

OFDM Orthogonal Frequency Division Multiplexing

OPEX Operational Expenditure

OTI Optimisation Time Interval

PDP Policy Decision Point

PEP Policy Enforcement Point

PASTA Poisson Arrivals See Time Averages

P-GW Packet Data Network Gateway

PRB Physical Resource Block

PSS Primary Synchronisation Signal

QoE Quality of Experience

QoS Quality of Service

RAN Radio Access Network

RAT Radio Access Technology

RE Resource Element

RF Radio Frequency

RLF Radio Link Failure

RRC Radio Resource Control

RRH Remote Radio Head

RRM Radio Resource Management

RSRP Reference Signal Received Power

SDR Software Defined Radio

S-GW Serving Gateway

SMS	Short Message Service
SNR	Signal to Noise Ratio
SON	Self-Organising Network
SSS	Secondary Synchronisation Signal
TBS	Transport Block Size
UE	User Equipment
UMTS	Universal Mobile Telecommunication System
U-plane	User Plane
VoIP	Voice over IP
WCDMA	Wideband Code Division Multiple Access
WiFi	Wireless Fidelity
WiMAX	Wireless Interoperability for Microwave Access
WMN	Wireless Mesh Network

ISBN: 978-87-93089-27-3

Published by:
DTU Fotonik
Department of Photonic Engineering
Technical University of Denmark
Ørsteds Plads, building 343
DK-2800 Kgs. Lyngby

Anna Zakrzewska received the M.Sc. Eng. Degree summa cum laude in information and communication technology from Wroclaw University of Technology, Poland in 2008. Afterwards she was with NTT Communication Science Laboratories in Atsugi, Japan and the European Commission Joint Research Centre in Ispra, Italy.

In 2010 Anna started the Ph.D. project in the area of multi-RAT and heterogeneous networks with the focus on resource management and Self-Organizing Networks (SON). At DTU she served also as the vice-chair of the IEEE Student Branch. Anna is a recipient of N2Women Student Fellowship 2013 and was recognized as a double finalist of the Google Anita Borg Memorial Scholarship in 2012 and 2013.

After the successful Ph.D. defence on February 24th, 2014, Anna joined the Department of Autonomous Networks and Systems Research at Bell Labs Alcatel-Lucent in Dublin, Ireland as a postdoctoral researcher.

DTU Fotonik
Department of Photonics Engineering