Radio Environment Map-Enabled Spectrum Sharing In Mobile Cellular Networks

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Submitted for the Degree of
Doctor of Philosophy
from the
University of Surrey

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July 2018

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Thesis submitted for the Degree of Doctor of Philosophy

Dedication

In loving memory of my grandmother ...

Executive Summary

The ongoing development of mobile cellular networks, supporting a wide range of applications and services with high data-rate and ubiquitous connectivity requirements, has resulted in a considerable increase in capacity demand. With the advent of next generation of mobile cellular networks, it is expected that the capacity demand to exceed far beyond the supply. This imminent capacity shortage has introduced impetus to identify practical solutions towards a more efficient utilisation of the spectrum. In this respect, various approaches under the umbrella of Spectrum Sharing (SS) have been explored. However, the incorporated techniques, along with some sets of strict assumptions, have imposed conservatively broad boundaries, known as Exclusion Zones (EZs)[1], to ensure interference protection, irrespective of the actual spatial-temporal utilisation of the spectrum. This has resulted in limited achievable gains, and consequently the conventional approaches are identified as inefficient for the real-world deployment. In fact, for the SS to be efficient and practically viable, there is a need for a paradigm shift towards a more dynamic mechanisms with a level of live spectrum usage awareness in the network, which can efficiently identify interference-free Spectrum Opportunities (SOPs) for sharing, and hence, the shortcomings and constraints of the conventional SS approaches can be mitigated. In this context, the aim of this thesis is to investigate a novel and efficient SS mechanism, in which Radio Environment Map (REM) technique as an enabler is applied. The REM captures near real-time spectrum utilisation in the network in temporal and spatial domains pro-actively, resulting in increased SOPs for sharing.

A comprehensive literature survey of the SS is provided in this thesis. The concepts, various authorisation regimes, along with their specifications and requirements are discussed. Moreover, the potential sharing deployment scenarios, as well as the use cases in which the mobile cellular networks can gain benefit from SS are pointed out. Further, having a robust view of State-Of-The-Art (SOTA) coordination protocols (i.e., centralised and sensing based approaches) and enabling techniques, the associated advantages, as well as the major shortcomings and challenges are investigated. This is followed by providing an in-depth insight into the SOTA proposals, approaches, the respective achieved gains, and the necessity for the enhanced/new techniques. Consequently four techniques, namely Inter-Operator Inter-Cell Interference (IO-ICI), the Sensing, Coordinated Beamforming, and REM identified as promising dimensions that can be substantially enhanced/applied in SS.

Focusing on the adoption of REM technique, a SS mechanism is proposed which exploits Received Signal Strength (RSS) along with spatial interpolation techniques to model temporal and spatial map of SOPs in the downlink of Long Term Evolution-Advanced (LTE-A), in a dynamic manner, subject to update rate in the order of LTE-A

[1] In order to protect victims (e.g. the incumbent) from harmful interferences, an exclusion zone and a protection zone are defined for each victim's site. An exclusion zone (or protection zone) is typically defined as a circle of few kilometres and where the victim sits at the centre. When necessary e.g. for victims located nearby a potential high density interfering deployment area (e.g. the LSA licensee' network), an additional and larger restriction zone can be defined [1].

time frame. The investigation is performed over the two well-known and distinctive spectrum sharing schemes; (1) Inter-Operator Spectrum Sharing (IOSS), and (2) Licensed Shared Access (LSA)[1]. For the scheme (1), the sharing players comprise two large-scale independently deployed Mobile Network Operators (MNOs), over the two standardised multi-MNO deployment topologies; non-collocated and collocated, in urban environment. The simulations are performed with high data rate real-time video streaming traffic traces. The simulation results are compared to the two SOTA approaches (i.e., centralised and sensing based approaches), as well as the LTE-A baseline. The simulation results demonstrate that the proposed REM-based sharing mechanism results in 23% improvement in Spectrum utilisation efficiency, 37.5% average system throughput, with respect to the baseline LTE-A, where the SS is not applied. Moreover, it is observed that the REM-based approach outperforms the two considered SOTA approaches. The cost of overhead, and computational complexity of implementation are found negligible.

In addition to IOSS, for the scheme (2) (i.e., the LSA), an arbitrary LSA incumbent as a worst case scenario (when no priori information is given) is considered. Through the the simulation results it is shown that the proposed approach reduces the size of EZs from considerable number of cells to a fewer numbers. The transmit power level does not need to to be reduced in majority of the cells in the network, and thus, the LSA bands can be utilised in a more dynamic manner. As a result, the overall system throughput is significantly increased with respect to the SOTA approach by 80%. However, this gain is subject to fast and reliable interface between two networks to allocate sufficient time for band evacuation[2].

Key words: Dynamic Spectrum Sharing (DSS), Inter-Operator Spectrum Sharing (IOSS), Licensed Shared Access (LSA), Mobile Cellular Networks, Spectrum Usage Awarness (SUA), Spetrum Uilization Efficiency(SUE) .

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[1]IOSS is defined when two or multiple Mobile Operators are involved in spectrum sharing. However, the LSA, is defined when one or multiple mobile operators share spectrum with a non-mobile communication system such as military.

[2]The time duration which is specified and agreed between the incumbent and mobile operators, to evacuate the shared bands upon request by the incumbent

Acknowledgements

First and foremost, I would like to express my sincere gratitude and appreciation to my supervisors, Prof. Klaus Moessner, and Dr. Seiamak Vahid, for their support and limitless patience throughout my PhD study.

Furthermore, my special thanks goes out to Dr. Dionysia Triantafyllopoulou for her valuable advices, since the early process of my PhD.

I would also like to acknowledge the support of my family and friends, who have been always there for me. This accomplishment would not have been possible without their consistent encouragement.

Declaration of Originality

I hereby declare that this thesis entitled “REM-Enabled Spectrum Sharing In Mobile Cellular Networks” is entirely my own work and that any material used from the other sources has been clearly identified and properly acknowledged and referenced. I am submitting this thesis for the degree of Doctor of Philosophy, from the Institute of Communication Systems (ICS), University of Surrey, Guildford, United Kingdom.

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July 2018

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List of Abbreviations

FCC	Federal Communications Commission, page 4
FDD	Frequency Division Duplex, page 31
FWA	Fixed Wireless Access, page 23
GAA	General Authorized Access, page 22
GT	Game Theory, page 38
IDW	Inverse Distance Weighting, page 75
IMT	International Mobile Telecommunication, page 21
IO-ICI	Inter-Operator Inter-Cell Interference, page iv
IoT	Internet of Things, page 1
ISM	Industrial, Scientific and Medical, page 26
ITU-R	International Telecommunication Union Radiocommunications, page 4
LAA	License Assisted Access, page 18
LSA	Licensed Shared Access, page v
LTE-A	Long Term Evolution-Advanced, page iv
LTE-U	LTE-Unlicensed, page 18
MAC	Medium Access Control, page 32
MBB	Mobile BroadBand, page 28
MDT	Minimisation of Drive Tests, page 73
MIMO	Multiple-Input-Multiple-Output, page 2
MME	Mobile Management Entities, page 50
mmWave	millimetre Wave, page 2
MNOs	Mobile Network Operators, page v
MOCN	Multi Operator Core Network, page 43
MORAN	Multi Operator Radio Access Network, page 43
MTC	Machine Type of Communications, page 1
MVNO	Mobile Virtual Network Operator, page 44
NB	Nash Bargaining, page 38
NE	Nash Equilibria , page 38
NN	Natural Neighbour, page 75
NRA	National Regulatory Authority, page 19
OAM	Operation, Administration and Management, page 48
Ofcom	Office of Communications, page 4

OPEX	Operational Expenditure, page 42
OSA	Opportunistic Spectrum Access, page 24
PAL	Priority Access License, page 22
PHY	Physical Layer, page 36
PMSE	Program Making and Special Events, page 47
PUs	Primary Users, page 23
QoE	Quality of Experience, page 57
QoS	Quality of Service), page 18
RAN	Radio Access Network, page 2
RAT	Radio Access Technology, page 31
RB	Resource Blocks, page 57
REM	Radio Environment Map, page iv
RIF	Radio Interference Field), page 73
RMSE	Root-Mean-Squared-Error, page 75
RNC	Radio Network Controller, page 34
ROI	Region of Interest, page 89
RRHs	Remote Radio Heads, page 51
RRM	Radio Resource Management, page 7
RRM	Radio Resource Management, page 32
SAS	Spectrum access system, page 22
SD	Spatial Domain, page 11
SG	Serving Gateway, page 50
SLAs	Service Level Agreements, page 29
SOPs	Spectrum Opportunities, page iv
SOTA	State-Of-The-Art, page iv
SS	Spectrum Sharing, page iv
SUs	Secondary Users, page 24
SUT	Spectrum Utilisation, page 11
TDD	Time Division Duplex, page 31
TD	Temporal Domain, page 11
TIN	Triangular Irregular Network, page 75
TPS	Thin Plate Spline, page 75

TTIs	Transmission Time Intervals, page 82
UMTS	Universal Mobile Telecommunications System, page 89

List of Symbols

alpha	binary coefficient for RB, page 82
E	Energy, page 80
eta	noise floor, page 83
H_0	Spectrum is not occupied, page 80
H_1	Spectrum is occupied, page 80
j	time index, page 82
k_i	sensor index, page 92
M	Number of cells in supply MNO, page 85
N	Number of cells in demand MNO, page 83
n	number of sensors in a grid, page 92
p	Location of interest, page 93
R	number of RBs, page 82
r	RB index, page 82
s	cell index, page 82
$SUT_{t,s}^{BW_{own}}$	Average spectrum utilisation of BW *own* in cell s at time t , page 83
t	time, page 82
TTI_t	t^{th} TTI, page 83
u	User index, page 82
UE_u	u^{th} user, page 83
V	Total number of sensors, page 89
x_{k_i}, y_{k_i}	sensors location, page 92
Z	RSS Measurments, page 93

Chapter 1

Introduction

1.1 Background

Today, a wide range of carrier-grade services with varying performance requirements is supported in mobile cellular networks. For instance, the broadband applications such as high-resolution video streaming, large cloud-based file transfers, with high data rates, require wide bandwidth for data transmission [2]. Moreover, by growing the use of mobile devices, such as smart phones to access diverse sets of such services and applications, as well as the development of new features, e.g., Machine Type of Communications (MTC), and wireless sensors in the Internet of Things (IoT) sector, the network load will be remarkably increased [2]–[4]. The massive growth in mobile data traffic has become a significant concern for the development of future wireless networks. It is estimated that in order to accommodate such amounts of traffic, a contiguous bandwidth from hundreds of MHz up to a few GHz will be required for the deployment of the 5th Generation (5G) systems [5], [6]. On the other hand, spectrum[1]

[1]Spectrum relates to the range of radio frequencies (that's the number of repetitions of the wave in a second) allocated to varieties of communications systems such as mobile industry for communication over the air. Behavior of the frequencies is different when passing through the air and this means that allocation of spectrum to the various communication systems needs to be regulated effectively rendering the spectrum useful. A communications signal, depending on the content of information, is transmitted on a set of frequencies called bandwidth.

as a fundamental part of wireless communication systems for data transmission is a scarce resource. The scarcity has proven to be a major issue across particular frequency ranges, spanning 100MHz to 6GHz, with desired propagation characteristics for the wide range of non-mobile spectrum users, e.g., military, radar, TV broadcasting, medical and event production, etc. [7]. Although the mobile cellular networks are expected to be capable of operating on sub-6GHz bands [2], these bands have already fragmented and assigned to the aforementioned spectrum users in an exclusive manner by the regulators [8], [9].

In this respect, the current generegation of mobile cellular networks, LTE-A specifications, support operation with bandwidths of up to 100MHz, thanks to multi-carrier functionalities such as Carrier Aggregation (CA) [10], [11], and also other techniques such as Multiple-Input-Multiple-Output (MIMO) [12]. Moreover, the deployment of millimetre Wave (mmWave) supported antennas are under investigations in order to facilitate utilisation of the higher frequency bands (e.g., 17-to-30, 60, and 90GHz) in mobile cellular networks, which have the potential to provide significant capacity improvements for both the Radio Access Network (RAN), as well as the backhaul [13]. In addition, the densification of small cells with low transmission power levels has been considered as a powerfull solution to improve frequency re-use. However, co-existence of small cells and macro cells in the same frequency bands introduces additional type of interference (i.e., cross-tier interference[1]). In contrast, dedicated allocation of bands to the small cells will lead to spectrum underutilisation and is not of interest to the MNOs. Besides, the deployment of small cells is subject to additional costs in terms of, e.g., high-speed backhaul and additional infrastructure requirements [14], [15].

A few more possibilities have been recently investigated to offer more of sub-6GHz spectrum range for mobile cellular systems. For instance, spectrum refarming has been broadly explored. In general, the term spectrum refarming refers to the migration of

[1] In multi-tier mobile cellular networks (i.e., macrocell, pico-cell, Femto cell, etc.), operating on the same spectrum bands, in addition to co-tier interference, cross-tier interference occurs. For example, a femtocell access point can cause interference to the downlink of a macrocell UE nearby. Also a macrocell UE can cause interference at the uplink of a nearby femtocell access point [14].

wireless communication systems of their spectrum, to the alternative frequency band(s) [16]. It follows the purpose of releasing the currently occupied bands with suitable propagation characteristics, for the communication systems that demand for it. In such cases, depending on the current occupancy status of each band and the level of importance of the respective incumbent, the spectrum regulator will have to evaluate if the refarming is necessary and viable, i.e., whether there is not any alternative way to accommodate the identified spectrum demands and also to justify the benefits that it is expected to provide. "Spectrum refarming often is a "last-thought" option of spectrum management, because it is likely to cause the most problems to set up and usually is the most lengthy to implement. Thus, when spectrum refarming is not feasible or desirable, SS can be an alternative option to spectrum refarming . In other words, SS and spectrum refarming can obviously complement each other." [17], [18].

Given above, the utilisation of the spectrum in a shared manner can be a promising solution. SS enables systems to exploit variable-size underutilised spectrum to meet their continuously growing capacity, as well as wide bandwidth demands, with lower license costs[1]. Overall, it results in an efficient utilisation of scarce spectrum. In this regard, various types of SS (also known as sharing schemes) are identified based on regulatory policies for the different involved systems (also known as sharing players). The candidate spectrum bands for sharing in sub-6GHz, encompasses, licensed and license-exempt bands[2], namely Wi-Fi, TV White Spaces (TVWs), and mobile cellular, etc. The deployment of SS is subject to meeting a set of pre-defined regulations and requirements, and can also involve various coordination protocols/techniques.

Recent research works clearly point out towards the impending necessity of SS. For instance, a number of international standardisation bodies currently focus on various

[1]Spectrum license costs resulting from SS (e.g., the LSA licenses) differs from the current auction based ones. In fact, the license costs of the shared bands could be lower due to restrictions in the conditions of utilisation of the band by the MNOs. The way of charging is via regular subscription fees, and can be based on business models, e.g., fixed or usage based prices [19].

[2]An "unlicensed" band is typically a new band, for which no request has been made and is not allocated to a specific service yet. The term license-exempt, however, allows operation with an exemption of licenses and it is referred to as "license-exempt" (such as in the 2.4 GHz ISM band) with no individual frequency planning/coordination. In some countries such as the US, the term unlicensed is sometimes used instead of license-exempt [20].

aspects of SS and its management. For instance, European Telecommunications Standards Institute (ETSI) focuses on SS, and plans to apply cognitive techniques such as REMs [21] (which is discussed later in this thesis), but the infrastructure sharing issues are not currently addressed (the different SS schemes will be discussed in detail Chapter 2). A recent study from the Third Generation Partnership Project (3GPP) specifications indicate increasing interest in various resource sharing scenarios, and how the MNOs can share common radio resources, according to identified RAN sharing scenarios, whether as a shared deployment or as a leased asset [22], [23]. The International Telecommunication Union Radiocommunications (ITU-R) is also soliciting solutions for the use of licensed "white spaces", as well as licensed-exempt bands with the aim of provisioning ubiquitous wireless connectivity [24].

On the regulatory front, bodies such as Office of Communications (Ofcom), and Federal Communications Commission (FCC) focus on the solutions that can open up of new bands when SS is performed among federal spectrum users, such as public sector, defence, etc., and MNOs. From Ofcom points of view, data offload can be performed efficiently through Wi-Fi for indoor capacity boost. However, in the case of outdoor, increasing Wi-Fi deployments can lead to the reduction of Quality of Service (QoS), and therefore a "tragedy of the commons"[1][2] may ensue. Moreover, with the emergence of MTC, "a huge number of new devices and services requires wireless connectivity, that can be delivered over mobile broadband networks, Wi-Fi or dedicated networks. The increased deployment of outdoor Wi-Fi for this purpose, can increase levels of interference and reduced quality of service. This has implications for the future viability of Wi-Fi for massive number of outdoor MTC applications." [2]. A release of Ofcom consultations [2] indicate that, SS as one possible supplement can address this problem.

In addition, SS has been broadly considered by European Union (EU) projects such as METIS [25]–[27] and SAPHAYRE [28], which parts of their work are discussed briefly

[1] For licence-exempt sharing in a given frequency band if too many uncoordinated outdoor Wi-Fi access points are deployed at a particular location and accessed by a large number of users, performance degrades and users will experience low data rates and dropped connections. This is an example of the "tragedy of the commons", where the difficulty in co-ordinated demand for a shared reduces the quality of experience for all users.

in this thesis. Besides, the major global research in spectrum sharing is studied in [29].

From the technical perspective, the main challenge of deployment is how to cope with the problem of co-channel interference, which occurs due to the utilisation of spectrum when two or multiple systems co-exist on same frequency band. This is known as a limiting factor to the promising gains that can be achieved through SS. The problem is common in the all SS schemes, however, is addressed through different techniques (also referred to as coordination protocols) due to the variable corresponding regulatory prerequisites.

For instance, through the LTE-U[1] sharing scheme,the Wi-Fi bands are made available for mobile cellular network uses under set of relaxed assumptions for interference protection. As the bands are not licensed to the Wi-Fi systems [29], exploiting a "fairness-based" (i.e., considering equal right of access) protocol under this assumption results in a satisfactory interference-free spectrum access for both sharing players [31]. Nonetheless, this is not a valid assumption for the other SS schemes. For example, the TVWs which are licensed to the TV broadcasters, are offered for sharing subject to meeting a pre-defined received power threshold to protect TV receivers from interference. The threshold value, however, considerably limits the potential geographical area of sharing . Though, research is conducted to improve the efficiency of this SS scheme via the techniques which make it more dynamic rather than a static threshold-based approach [32].

The deployment of other two SS schemes, comprising IOSS and LSA, is even more challenging compared to the sharing of the TVWSs. The IOSS is defined when two or multiple MNOs share their licensed bands. The LSA scheme on the other hand, facilitates utilisation of the bands (currently sub-6GHz) licensed to non-mobile systems (termed incumbent) for mobile cellular networks uses, in a fully harmonised manner; i.e., in a non-interfering basis, with access guarantees. The challenge is transparent, as

[1] The LTE-U is referred to as LTE/Wi-Fi coexistence, in which, it is intended to allow the MNOs to deliver their traffic via accessing the unlicensed 5 GHz frequency in a shared manner with the Wi-fi networks (running their own network infrastructure and not offload to the Wi-Fi) [30].

in the case of TVWSs, the TV transmitters and receivers are stationary with known locations, fixed and known transmit power, and the communication mode is unidirectional (broadcast). In contrast, in IOSS and LSA schemes with various traffic types, the sharing players are not always still, the transmission is bidirectional, and the transmit power levels can be variable. These characteristics result in highly dynamic spectrum utilisation pattern in temporal and spatial domains. The strict regulatory rules for interference avoidance, and on the other hand, lack of real-time knowledge of dynamic spectrum utilisation of the sharing players, resulted in investigating conservative sharing protocols with limited gains. Hence, in this thesis, these two most challenging, yet potential SS schemes are investigated, as they contribute to provide additional licensed spectrum for mobile cellular networks, as well as to improve efficient utilisation of scarce licensed spectrum.

1.2 Motivations and Objectives

The conventional methods were dimensioned based on the knowledge of spectrum availabilities on a cell level basis, irrespective of the spatial-temporal spectrum utilisation in the adjacent cells. Hence, conservative coordination protocols have been adopted to ensure interference protection for all sharing players, mainly the actual owner of the spectrum. The impacts of theses approaches were justified for the small scale deployment scenarios mainly (mainly for two cells). For example, the SOTA of IOSS-work perform based on either centralised coordination protocol [33], or solely sensing technique as in [34], thus, lack of awareness of spectrum utilisation in all surrounding cells in the mobile cellular networks for detection of interference-free SOPs, resulted in low/no spectrum sharing gain over large-scale networks.

Moreover, in the SOTA of the LSA scheme (which is discussed in the following chapters), through the available statistical propagation models, considering a predefined interference threshold, the potential interfering radius imposed by the cellular network is approximated. In this respect, to avoid any probable interference, most conservative interference threshold and propagation model (as a worst case scenario) are considered irrespective of actual presence of the incumbent in the area. This has resulted in the mobile cellular and the incumbent networks to widely overlap, making LSA scheme almost inefficient. These call for adoption of a more dynamic technique(s) that is capable of detecting and monitoring SOPs over large scale areas rather than just a specific cell/area. In this regard, in this thesis, the REM techniques is applied in SS.

The term REM is defined as a set of network entities and associated protocols that trigger, perform, and store the geo-located measurements of the received signal strength. The measurements are processed and compared to a predefined interference threshold, and specify whether any location of interest is a potential interfering area. Such measurements are typically performed by User Equipment (UE), or dedicated sensors, and are stored and treated in a database, which facilitate tracking dynamics in the network. The post-treated REM data is then provided to the Radio Resource Management (RRM) functionalities of mobile cellular networks, as additional capacity that can be allocated to the UEs based on the demand, and on a temporary basis. In the context of SS, thus, the REM is a powerful tool that provides synthesised view of the networks for monitoring purposes. The main rational behind applying the REM in this thesis, originates from the fact that in contrast to the SOTA, REM is a combination of sensing, statistical interpolation techniques, and in a coordinated manner (than can be a centralised database), which builds a map of temporal-spatial utilisation of the network in large-scale, resulting in more efficient SOP awareness, as well as an interference protection scheme. A generic overview of the REM concept is provided in Chapter 3 of this thesis.

Overall, the aim of this thesis is to investigate feasibility of REM technique to enhance performance of dynamic SS comprising IOSS and LSA schemes, and to analyse the impact of REM-enabled SS mechanism on the LTE-A system performance, and consequently to identify problems, and come up with solutions. More precisely, in this thesis the following objectives are met:

- To model REM, received signal strength measurement data is collected via sensors in specific locations, and in conjunction with Kriging interpolation technique, spectrum usage map of the entire network is created.

- To apply REM for SS, the REM data is utilised by a third-party entity as a real-time SOP awareness and is allocated for SS (both IOSS, and LSA) upon demand. Interference level is monitored considering a predefined threshold.

- To evaluate the impact on LTE-A performance, SUE, and bandwidth/capacity/throughput, for the mobile cellular networks are measured.

- To identify REM problems, the gain vs. overhead and delay trade-off is evaluated.

This approach is investigated for the two distinctive and challenging SS schemes: (1) IOSS, and (2) LSA. It is worth mentioning that the REM has not been applied in the SOTA, for these two SS schemes, to investigate impact of the REM-Enabled SS on mobile cellular networks performance. Hence, no work has been done to assess its superiority over the conventional approaches yet.

1.3 Overview of Contributions

The main contributions of this thesis are summarised as follows:

1. **Licensed Spectrum Sharing Schemes for Mobile Operators: A Survey and Outlook**

   A comprehensive survey of SOTA that investigates various aspects of SS is conducted. In the initial step, an in depth study of existing licensing/authorization regimes, their specifications and requirements are provided. This study helps to get a broad overview of all authorised possibilities of SS. Further, the potential SS deployment scenarios in mobile cellular networks, which can benefit from SS are identified and categorised. From a technical perspective, a detailed survey of the several existing coordination protocols applied in the SOTA of SS (mainly the IOSS and LSA), their advantages and shortcomings are discussed. This is followed by the investigation of business aspects/requirements of SS for the practical implementations.

Having an in depth background of the SS concepts, the SOTA of the proposed approaches for IOSS category based on the deployment scenarios which learned earlier, are critically discussed. In this study, the achieved gains are mainly targeted against the requirements to investigate their viability for the practical deployment. The same investigation also is carried out for the SOTA LSA framework, which is now a hot topic and in its initial steps for the deployment. As the outcome of this survey, several existing challenges in these two important SS schemes are identified, and various potential research directions that can tackle limitations of some of these challenges are recommended for further investigation.

The four promising directions, which are identified for enhancements/investigation to be applied in SS, comprise: IO-ICIC, Coordinated Beamforming, sensing, and REM. The first two, can mainly be applied in IOSS (when only the MNOs are involved). However, the latter is found as a potential technique in the context of both IOSS and LSA schemes. This thesis serves as an introductory guide for application of REM in SS (IOSS and LSA), and it provides insights towards a more efficient and practically viable SS mechanism. The enhancements of sensing technique, as one of the main functionalities of the REM, will be one possible option in the future works of this thesis.

Overall, the end goal of this survey is to provide an insight into practically viable SS schemes that enable the MNOs to access sub-6GHz licensed bands in an efficient shared manner. It is emphasised that, in this survey the impact of spectrum sharing in mobile cellular networks is investigated, and therefore, the sharing schemes in which at least one sharing player is an MNO are considered. This contribution has been published in [29] and [35], and located in the Chapter 2 of this thesis.

R. H. Tehrani, S. Vahid, D. Triantafyllopoulou, H. Lee and K. Moessner, "Licensed Spectrum Sharing Schemes for Mobile Operators: A Survey and Outlook," *IEEE Communications Surveys & Tutorials*, vol. 18, no. 4, pp. 2591-2623, Fourthquarter 2016.

2. **Survey of Radio Environment Map Techniques**

A study of SOTA REM is conducted. The two main methodologies are identified comprising sensing-assisted propagation-based, and sensing-assisted interpolation based REM. The use cases (including: TVWS sharing, coverage hole detection in the LTE-A specifications, etc.) are identified along with the common challenging issues of the deployment. Moreover, a set of important assumptions that have been made to facilitate implementation of REM are pointed out. In addition, it is found out that the SOTA performance evaluation, mainly is focused on the performance of REM, and not the impact of applying REM in the uses cases mentioned above. Overall, the end goal of this study is to get a broad overview of all possibilities of the REM deployment to identify the most reasonable method (considering the characteristics of the mobile cellular networks) for the SS. This contribution is submitted for the publication, and is located in the Chapter 3 of this thesis.

R. H. Tehrani, S. Vahid, and K. Moessner, "Survey of Radio Environment Map Techniques," *IEEE Communications Surveys & Tutorials*, to be submitted.

3. **A Radio Environment Map-Enabled Spectrum Sharing Mechanism for Mobile Cellular Networks: Feasibility and Performance Analysis for IOSS**

The IOSS problem in mobile cellular networks is formulated and spectrum cartography[1] in the context of REM is exploited to address this problem. More specifically, a Received Signal Strength (RSS) aided approach is considered. In addition, as of in REM, to minimise the burden of measurements in large scale areas that the observations/measurements are not available, out of various types of interpolation techniques in SOTA of REM, Kriging, is applied (the detailed discussion is provided

[1] Spectrum cartography is reffered to the context of discovering spectrum holes in space/time that can be exploited in Cognitive Radio Networks (CRNs).

in Chapter 3 and 4). Thus, it performs based on measuring and estimating the SOPs over any area of interest on a real-time basis and under realistic traffic pattern conditions, rather than adopting the conventional centralised approach [33] which considers Spectrum Utilisation (SUT) in a cell of interest in mobile cellular networks, or in [34], in which the sensing technique is applied. In other words, this approach takes into account both Spatial Domain (SD) and Temporal Domain (TD) SUTs and generates a map of interference-free SOPs.

To assess the potential gains of the proposed mechanism, a system level simulator underlaying the legacy LTE-A is developed. The simulator provides a detailed modelling of the SS procedures including; REM dissemination, the shared resource scheduling, and interference management, in multi-cell multi-MNO scenario. Without loss of generality, and for the simplicity of simulation and analysis, the number of involved MNOs in SS is limited to two. Moreover, the two possible deployment topologies of the two involved MNOs are considered which include: collocated and non-collocated[1]. These topologies are justified by the 3GPP [36] multi-MNO standardised architecture. The real-time video streaming traffic model is adopted with a high data rate requirements. Our simulation results show that average system throughput of 37.5% is achieved compared to the baseline of LTE-A (and higher throughput compared to the conventional approach in [33]), in urban environment, under non-correlated traffic pattern between the two involved MNOs, in a no-mobility scenario. The overhead and computational complexity as an inevitable part of this approach are found negligible. The delay is assumed negligible[2] so that does not make negative impact on the validity of the SOP information.

In addition, it is found out that through this approach, the topology of MNOs does not impose critical impact on the SS gains. This is in contrast to the conventional approach [33] where in non-collocated deployment multiple cells were involved. In the SOTA of IOSS, (mainly [33] is considered), it is stated that identification of the

[1] Collocated is reffered to as deployment of two MNOs with 100% network overlap. Non-collocated is refered to as partial overlap of the two MNOs

[2] More detail is discussed in Chapter 3.

SOPs in non-collocated deployment (where one BS/cell/site of interest geographically overlaps with multiple BSs/cells/sites that are operating in the same spectrum band) is very challenging compared to the case of collocated deployment. In this approach SS is managed via a centralised entity which collects SOP information from each BS/cell/site. Upon request for shared spectrum in any BS/cell/site of interest, as the centralised entity does not have any view of where (geographical point of view) the shared spectrum is going to be used, it requests to all the overlapped BSs/cells/sites to evacuate the same spectrum band (if there is any SOP). Due to this reason, it is stated that; it is almost impossible (or very limited) to find free spectrum (i.e., SOPs) for SS in all the overlapped cells and consequently, SS gain in this topology is very limited. However, the advantage of REM approach is that, the SOPs/spectrum usage is monitored on a geographical area basis (and not the cell level). Thus, the gain is not dependant on the topology of the MNOs, whether the topology is collocated or non-collocated, the SOP information is available for any area of interest.

Through the REM based approach, the SUE 23% improvement (averaged over the cells and entire simulation time) is achieved compared to LTE-A baseline when no SS is applied.

Given a general fact that the upper bound capacity gain that can be achieved through the IOSS scheme depends on the traffic load correlation of the MNOs in any area of interest (irrespective of any mechanism applied), the LSA schemes is further investigated by which, wider capacity/bandwidth can be achieved.

4. **A Radio Environment Map-Enabled Spectrum Sharing Mechanism for Mobile Cellular Networks: Feasibility and Performance Analysis for LSA** The applicability of REM in the LSA scheme is investigated. The same methodology as of IOSS is applied, under the different challenges and assumptions. More specifically, this approach detects the presence of the incumbent and identifies the potential interfering geographical area, and that how many cells (which part of cell)

should be deactivated as the LSA bands are revoked by the incumbent dynamically. This is in contrast to the the SOTA approaches which approximate the potential interfering radius through the available statistical propagation models, considering a predefined interference threshold. As not much information (mainly actual radioelectric parameters, such as antenna height, terrain based or over the air, etc.) is known, conservative propagation models are applied to estimate a worst-case scenario of interfering signal, which fail to identify a more accurate estimation of overlapping area of incumbent with mobile cellular networks, resulting in low capacity gain out of LSA scheme. Thus, even though the presence of the incumbent is informed through an interface (any type of backhaul), a wide coverage area of cellular network is identified as an interference zone. However, the incumbent may overlap only with part of the cell.

In addition, through this approach, when the interfering area is identified, there might be no need to entirely shutdown a cell. In this case, in the identified area, and assuming multi-band supported cell, the traffic can be steered to the exclusive bands. Therefore, any service disruption probability (e.g., the data packet loss probability) incurred due to the band revocation by the incumbent is mitigated.The LSA scheme is implemented between one demand[1] MNO in the LTE-A downlink under the same assumptions described in the previous approach, as well as an arbitrary incumbent.

The LSA bands are available to be utilised over the entire coverage area of the demand MNO. On the other hand, the incumbent is assumed to follow a dynamic and random activity pattern, resulting in geographical overlap with the demand MNO which may range from part of a single cell up to multiple cells, occasionally. The location and power of incumbent are assumed unknown due to confidentiality, which forms the worst-case scenario of LSA scheme. This scenario is justified by a pilot trial carried out in Italy [37], [38].

Our simulation results show that this approach increases the chance of more ge-

[1]The term demand is used in the entire thesis for the MNO which requests for shared spectrum. The term supply is also referred to as the MNO or incumbent that offers shared spectrum to the demand MNO.

ographical locations/cells to keep serving their users over the LSA bands, and in general reducing EZ by from 41-cells to 3-cells compared to the propagation based methods and service disruption probability in the context of total system throughput increased upto 80%. It is emphasized that the this approach identifies and decreases EZs, and therefore the post processing reactive tasks of LTE-A for band evacuation; such as power adaptation, load balancing or traffic steering to the adjacent cells are not considered.

The last two contributions are submitted for the following publication, and is located in the Chapter 4 of this thesis.

R. H. Tehrani, S. Vahid, and K. Moessner, "A Radio Environment Map-Enabled Spectrum Sharing Mechanism for Mobile Cellular Networks: Feasibility and Performance Analysis," *IEEE Trans. on Wireless Commun.*, to be submitted.

1.4 Thesis Structure and Outline

The remainder of this thesis is structured as follows:

Chapter 2: Background and State-of-The-Art Spectrum Sharing

A broad survey of SOTA of SS is presented. As a fundamental part of this study, the concepts, various types of SS, requirements and challenges are pointed out. Narrowing down to the two specific SS schemes, i.e., IOSS and LSA, SOTA approaches are critically discussed, and possible options for further enhancements are identified. Based on the lessons learned from the survey, one potential technique called REM is selected to investigate its applicability on the IOSS and LSA.

Chapter 3: REM Methodology

The introductory and essential information about REM technique is provided, including its functionalities, methodologies, and SOTA techniques for implementation.

REM-Enabled Inter-Operator Spectrum Sharing]

The applicability of adopting REM in IOSS is investigated from various aspects. The proposed scheme applies both RSS measurements, and the Kriging interpolation technique to build the map of SOPs in the mobile cellular networks. Through this approach the system acquires knowledge of TD-SD of SUT, and hence, more interference-free SOPs for SS is provided. A system level simulator is developed to evaluate the performance of this approach against the SOTA, and LTE-A baseline (without SS) for two individual multi-MNO deployment topologies, i.e., collocated and non-collocated. The simulation results are analysed and discussed at the end of this Chapter.

Chapter 4: REM-Enabled Licensed Shared Access

The applicability of adopting REM in the LSA, is investigated. With the main objective of minimising the reduction of EZs. The detailed information regarding the system model along with the assumptions are discussed. The proposed scheme is evaluated against the conventional propagation-based LSA with the presence of an arbitrary incumbent. System level simulation results are provided and discussed.

Chapter 5: Epilogue

The main findings and insights acquired by the investigations in this thesis are summarised and concluded. In addition, some potential future research directions are outlined to cover the open issues related to the REM-Enabled SS mechanism. The main focus is on moving forwards the adoption of this mechanism to the next generation of mobile cellular networks, particularly 5G. Besides, it is expected that this scheme can efficiently enhance the performance of LAA scheme.

1.5 Publications

The research carried out in this Ph.D. has resulted in the following publications:

- R. H. Tehrani, S. Vahid, D. Triantafyllopoulou, H. Lee and K. Moessner, "Licensed Spectrum Sharing Schemes for Mobile Operators: A Survey and Outlook," *IEEE Communications Surveys & Tutorials*, vol. 18, no. 4, pp. 2591-2623, Fourthquarter 2016.
- R. H. Tehrani, S. Vahid, and K. Moessner, "Survey of Radio Environment Map Techniques," *IEEE Communications Surveys & Tutorials*, to be submitted.
- R. H. Tehrani, S. Vahid, and K. Moessner, "A Radio Environment Map-Enabled Spectrum Sharing Mechanism for Mobile Cellular Networks: Feasibility and Performance Analysis," *IEEE Trans. on Wireless Commun.*,to be submitted.

[White Papers]

- R. H. Tehrani, S. Vahid, and K. Moessner, "Licensed Spectrum Sharing Schemes for Future Mobile Communication Systems," White Paper for 5GIC-WA6, Mar. 2015.

Chapter 2

Background and State-of-The-Art Spectrum Sharing

In this Chapter, an in depth survey of existing licensing/authorisation regimes, their specifications and requirements are conducted. Moreover, a detailed discussion of existing coordination protocols applied in the SOTA SS (i.e., IOSS and LSA), their advantages and shortcomings are presented. In addition, potential deployment scenarios in mobile cellular networks, which can benefit from SS are identified. This is followed by a brief overview of business and regulatory aspects of SS for the practical deployment. Furthermore, an extensive study on various proposed approaches in IOSS, and LSA framework in the literatures is conducted and their achieved gains[1] are argued against their viability for the practical deployment and respective challenges. The outcome of this study includes several potential research directions for further enhancements.[2]

[1]Numerical values are discussed subject to availabilities in the related works.

[2]In the entire thesis the following terms are used interchangeably:

- Cell and Base Station (BS)
- Mobile Cellular networks and Mobile Operator Network (MNO)
- Spectrum Opportunities (SOP) and Spectrum availabilities and idle spectrum
- User and User Equipment (UE)
- Licensed Spectrum Sharing, and Spectrum Sharing (SS) (both include IOSS and LSA, unless stated otherwise)
- Resource Block (RB), and spectrum, and bandwidth

2.1 General Concepts

2.1.1 Spectrum Access Methods and Authorisation Regimes

In this Section, the classification of various available authorisation regimes (licensing policies), which determine the allowable levels of SS between sharing players are explained. These authorisation regimes are defined by the respective spectrum regulators at national/international level. In general, authorisation regimes are characterised and distinguished by the following parameters: level of spectrum access guarantees to meet capacity related Quality of Service (QoS) requirements, spectrum license fee, and spectrum utilisation efficiency, targeting different spectrum ranges. In fact, service providers (MNOs in the scope of this thesis) can apply one/combinations of the licensing policies depending on their level of QoS and interference sensitivity, budget and spectrum requirements.

The SS in future cellular systems (namely 5G), has a scope far beyond that addressed in the previous studies of CRNs [39]. New sharing policies have been defined. Some of them such as LSA have more strict rules concerning access and interference protection guarantees compared to the (traditional) CRNs. Other sharing policies such as License Assisted Access (LAA), LTE-Unlicensed (LTE-U) have been offered, which all add broader frequency ranges to 5G, In CRNs, radios are capable of learning/monitoring the environment and change their transmission parameters adaptively based on the observations. In this way, the cognitive radios capture spectrum opportunities (also known as "spectrum holes") with the aid of wide range of detection techniques/protocols (e.g., Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA) in Wi-Fi, in a dynamic manner. This helps improve SUE, and therefore mitigates the desired-spectrum scarcity problem. However, access to the bands is opportunistic and in an unlicensed manner, i.e., with zero interference protection guarantees when multiple service providers coexist. Due to the fact that service providers with strict QoS requirements will need to access the shared bands in a more deterministic manner (rather than opportunistic),

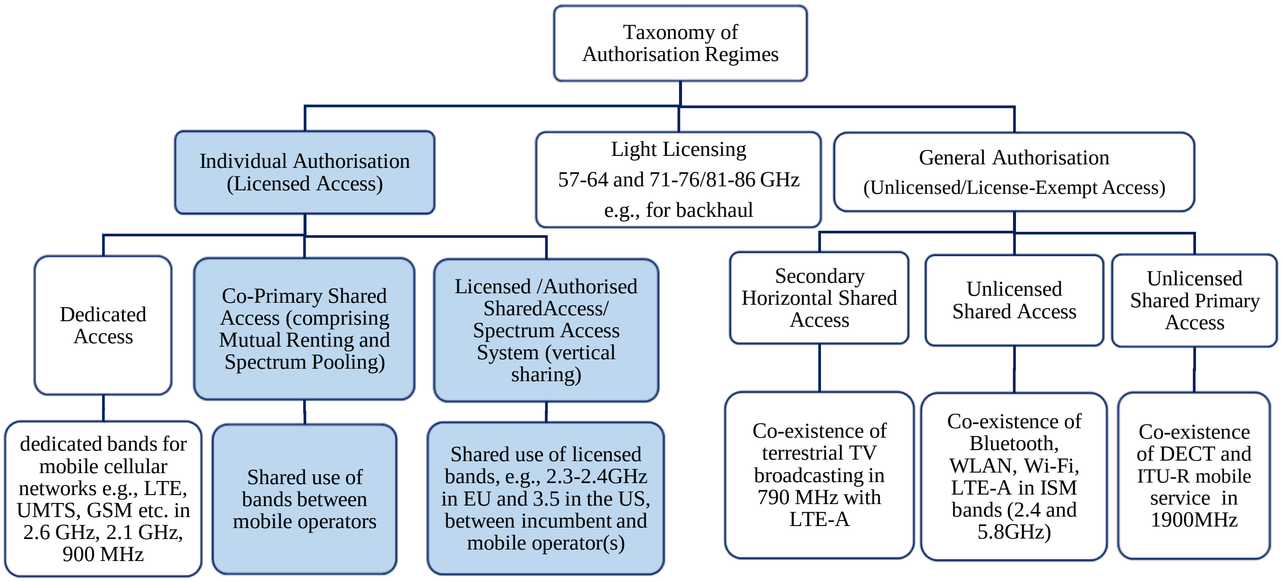


Figure 2.1: Taxonomy of spectrum access methods and authorisation regimes [25], [40] (The shaded blocks represent the scope of this thesis)

new licensed spectrum access methods have been offered by the regulatory bodies. In the following subsections, all the currently available authorisation regimes are discussed in detail.

Authorisation regimes can be divided into three main categories; A. Individual Authorisation, B. Light Licensing, and C. General Authorisation. A classification of authorisation regimes and respective access methods is illustrated in Figure 2.1.

A. Individual Authorisation (Licensed Access)

In this type of authorisation, the right of access, known as license, to the particular part(s) of the spectrum is granted on an exclusive basis. Therefore, only the license holder is authorised to exploit the bands in time, frequency and geographic region. In each country, the license is usually granted by the respective National Regulatory Authority (NRA), for a particular time period through an auction. The frequency bands that are allocated under this authorisation regime are known as licensed bands. The different levels of access to the licensed bands and possible sharing schemes are identified as follows [25]:

1. **Dedicated Access:** Dedicated level of access to the licensed bands implies that the license holder can operate on these bands exclusively. Hence, this access mode is advantageous for the license holder, as there will be no other interfering system(s) operating in such bands with the same priority level, and therefore, access to the spectrum as well as QoS requirements are guaranteed at the cost of high license fees [17]. However, this access method leads to waste of licensed spectrum, when the spectrum is not utilised in a particular time period or in a specific location(s), while other service providers (such as MNOs) face capacity shortage. Therefore, the possibility to share the licensed spectrum chunks (variable in amount) with other service providers in a licensed manner and achieve some revenue has been offered. It is worth noting that, due to the sensitivity of the sharing players in terms of interference protection and guaranteed access to the licensed bands, licensed spectrum sharing schemes require adoption of robust coordination protocols among sharing players which is discussed in detail later. The currently available licensed access methods to the licensed bands are listed below.

2. **Co-Primary Shared Access:** Co-primary use of spectrum implies that the license holders, subject to the permission of the respective NRA, jointly use their licensed spectrum (typically part of it) in a shared manner through mutual agreements among them or under obligation by the respective NRA. It should be noted that, based on this method the users of different MNOs have equal access rights without priorities being set by the regulations [41]. The two relevant access methods under the umbrella of co-primary shared access are as follows:

   a. **Spectrum Pooling:** The NRA, instead of dedicated allocation of the particular licensed bands to an MNO, allocates them to a number of MNOs (limited number). This access mode provides an opportunity for the MNOs to acquire additional licensed bands on a shared basis, where/when it is needed, and therefore improves spectrum utilisation efficiency. Under bi/multi-lateral agreements among MNOs, specific rules can be set to achieve the fair/reasonable level of spectrum access guarantees, as well as preventing aggressive/un-coordinated re-use of spectrum. However, simultaneous access to the bands for all participating MNOs still proves insufficient[1] to meet the capacity demand. This access scheme, can be beneficial for the MNOs that in conjunction with exclusive spectrum to fulfil their QoS targets and capacity demands, with the considerably lower license fee (compared to auction-based license fees), together with their own dedicated licensed spectrum [25], [42].

b. **Mutual Renting:** In this access mode, licensed bands that have been already allocated to an MNO on an exclusive basis, can be rented to another MNO(s) subject to the permission of the respective NRA. This provides the MNO with an additional source of revenue from its temporarily unutilised spectrum, and improves spectrum utilisation efficiency. This scheme is advantageous for an MNO that faces temporal capacity shortage and requires more licensed spectrum to accommodate high data rate/capacity requirements with guaranteed QoS and cheaper license fee compared to the case of exclusive access. However, in this access method, the spectrum owner has pre-emptive priority to access its own spectrum at any time, in contrast to the case of spectrum pooling. Therefore, this access scheme seems to be more beneficial when the spectrum is expected to remain unutilised over a long period of time [25], [43], or by the instantaneous spectrum opportunity detection, thanks to traffic diversity in time/location.

3. **Licensed /Authorised Shared Access (Vertical Sharing):** This sharing scheme is categorised as follows:

   a. **Authorised Shared Access (ASA):** ASA has been developed with the aim of using specific International Mobile Telecommunication (IMT) bands, initially 2.3GHz (in the U.K.) and 3.8GHz (in the U.S.), in a shared and non-interference basis for mobile services [16], [17].

[1] This means that shared spectrum that can be achieved from pooling itself can not be enough for the MNOs, but in conjunction with exclusive spectrum it can help MNOs to satisfy their QoS.

b. Licensed Shared Access (LSA): LSA is an extension of ASA concept, which is proposed by the Conference of European Postal & Telecommunications (CEPT), Electronic Communications Committee [44], in order to facilitate the use of favourable licensed bands for mobile communications use in a fully harmonised manner (non-interfering basis and guaranteed access) and under a licensing regime with the purpose of improving spectrum usage efficiency with lower spectrum license fee compared to the case of exclusive access. However, the deployment of such new access methods may impose additional costs for sharing players. According to this access scheme, a non-mobile communication license holder can share spectrum with one or more mobile communication networks under certain rules and on a non-interfering basis. The details of the spectrum usage are subject to an individual agreement and permission which are determined by the respective NRA [45], [46].

c. Spectrum Access System (SAS): SAS is rather a similar framework to the LSA, defined by the FCC and currently targets the 3.55-3.7GHz bands to improve spectrum utilisation efficiency. In the context of SAS, however, three tiers are identified. The first tier, similarly to the LSA framework, is the incumbent system. The second tier is called Priority Access License (PAL), which can be an MNO. In contrast to the LSA, a third tier which is called General Authorized Access (GAA) has also been defined which provides lower access guarantees than the PAL. The level of interference protection between the tiers is reduced top down. However, similar to the LSA, SAS offers lower license fee than exclusive access [47].

B. Light Licensing

The term light licensing refers to a more flexible and simplified regulatory framework of issuing spectrum authorisations compared to fully exclusive authorisation. This access method is expected to be applied to frequency bands where the risk of interference is low [48]. However, in order to preserve a certain level of protection, it is optimal to avoid interference to already existing users. Examples of the target bands that seem to be reasonable to be used under this access mode are the 60GHz (57-64GHz) and 80GHz (71-76/81-86GHz) bands whose propagation characteristics facilitate the operation with minimum risk of interference, as well as the provision of high data rate capacities [40]. These bands can be utilised in wireless service links, e.g., the backhaul, as well as the mmWave antennas technologies. Besides, the 5.8GHz band in the U.K. has recently been introduced as a candidate under this access regime to support broadband wireless access [49]. In South Korea, spectrum bands in 24-27GHz and 64-66GHz have been cleared for the use in the backhaul/small cells [50]. The band 57-64 GHz is allocated to the fixed service on a worldwide primary basis. In particular, this band, in conjunction to the adjacent 64-66 GHz band, seems very suitable for very short distance links deployed in dense scenarios (approximately 1 km) [25].

The band at 5725-5850 MHz (Band C) which is already in use by other services, including amateur-satellite, weather and military radars, can be used for the Fixed Wireless Access (FWA) services, with particular application in areas where broadband is unavailable through standard delivery platforms. FWA operating at band C can be used to provide broadband services to a range of business, private and public users. Under a normal licence-exempt regime, it would not be possible for Ofcom to provide adequate protection for these services while permitting the higher power levels needed for provision of a viable fixed wireless access service on a shared basis. Therefore Ofcom has put in place a light-licensing regime. Access to 5.8 GHz band C for FWA users is currently permitted throughout the UK on secondary basis, provided that no interference is caused to the Primary Users (PUs) in the band. Ofcom reserves the right to introduce geographic EZs if this becomes necessary to protect the primary users in band C. This regime requires a minimum payment and registration. The fee is £1 per terminal, subject to a minimum fee of £50 per licence. There is no maximum limit on how many terminals you can have on one licence [51], [52].

This type of access, under current classifications of the regulatory regimes, falls between the individual and general authorisations in a way that is based on different sharing parties, it can lie either in the general or individual authorisation regimes.

C. General Authorisation (License-Exempt/Unlicensed Access)

The term license-exempt access (also called unlicensed) is defined where a set of users (and respective service providers) co-exist and are able to utilise the specific frequency bands opportunistically, and with equal priority rights of access [48], [53]. The bands, which are made available for shared use under this authorisation regime, can range from licensed to license-exempt bands, such as, narrowband licensed TVWSs, Wi-Fi bands in 5GHz, etc. The users operating under this licensing regime must be certified and comply with the general defined technical regulations. Although no/minimum interference protection is offered to the users (i.e., unpredictable QoS guarantees), the spectrum cost is basically low to nearly zero [25], [48].

Various schemes, which are defined under this authorisation regime, have been widely applied in CRNs under Dynamic Spectrum Access (DSA) and Opportunistic Spectrum Access (OSA) contexts and based on prioritisation of the users into primary and secondary hierarchies. The well-known techniques in DSA schemes are as follows: 1) underlay, 2) overlay, 3) hybrid underlay-overlay, and 4) interweave[1] [55], [56]. In both underlay and overlay access modes, Secondary Users (SUs) are authorised to use the shared spectrum regardless of the presence of PUs. However, the SUs are subject to a condition that the level of potential interference to the PU does not exceed a predefined threshold, which can be managed by adapting the power level of SUs, or performing any type of coordination with the PU to avoid performance degradation. In contrast, in the interweave approach, SUs can find

[1]In the interweave DSA model, an SU can transmit only on a spectrum band where the PU is not active, and has to jump onto different bands over time. In the underlay DSA model, an SU can transmit on a spectrum band no matter the PU is active or not, but at a low power on each band to limit interference. In the overlay DSA model, an SU can transmit on a spectrum band with a large power even when the PU is active [54].

and utilise the free bands in which a PU is not active, which could be in any or combination of temporal, frequency, and spatial domains in an opportunistic way [54].

Various enabling techniques that have been studied extensively in CRNs, comprise: wide ranges of sensing techniques [57], geo-location database, beacon signalling, etc. [58], in order to enable SUs to exploit the PUs' spectrum in an opportunistic manner. Besides, for the prediction of PUs activity, various theoretic models are available such as "Discrete-time Markov process", "Continuous-time Markov chain", "game-theoretic" models, etc. [59], [60]. The characterisation of access methods, which conform to this authorisation regime with their corresponding use cases are explained below.

a. **Secondary Horizontal Shared Access:** The licensed bands are shared by the PUs among a diverse set of SUs in a horizontal[1] and opportunistic manner (i.e., with the low levels of access guarantees and interference protection) [61]. A number of interference avoidance schemes have also been proposed such as those in [62] and [63], to avoid interference when multiple SUs need to coexist with PUs. In this regard, cognitive techniques such as sensing, geo-location database, etc. have been applied. The TVWSs and Digital Video Broadcast in 700MHz bands are the most common candidates to be used under this access method with lower license fees [25]. Spectrum leasing policies have been applied to offer a more robust (in terms of access guarantees) form of OSA/DSA schemes in licensed bands in CRNs [64], where for example, the white spaces are leased to SUs subject to pre-negotiation with the PUs. The PUs determine the cost of white spaces based on parameters such as; channel access time, type of SUs, etc., to increase their monetary gain, however, the PUs need to perform continuous

[1] The terms vertical and horizontal are used for hierarchy of right of access to the bands. Assuming Primary-Secondary hierarchy of right of access to the shared bands, primary and secondary service providers are located vertically (primary is located above the secondary), and two/multiple secondary service providers are located in the same level (the term horizontal here refers to equal/same level of access for multiple secondary service providers).

monitoring of SUs' activities. The SUs, on the other hand, select the suitable PUs for optimal channels according to their QoS requirements, the fee of white spaces, and required channel access time.

b. Unlicensed Shared Access: The license-exempt frequency bands under this access scheme are authorised to be used by various types of users/services with equal access rights. The utilisation of license-exempt bands are subject to specific transmission power constraints in order to minimise the interference [39], however, low/no interference protection and access guarantees are offered. This type of access is also known as Collective Use of Spectrum (CUS) [39]. The license fee is nearly zero though. Currently, the associated bands comprise the 2.4GHz and 5GHz in the Industrial, Scientific and Medical (ISM) bands, where different services such as Wi-Fi, Bluetooth, co-exist [25]. Such bands in Wi-Fi networks for the purpose of data offloading have been increasingly utilised [65] by 3G/4G network operators utilising their own Wi-Fi networks referred to as "Carrier-grade Wi-Fi". The LAA and LTE-U, are the defined access schemes under this category.

The idea of extending LTE-A specifications to operate in license-exempt bands has received considerable attention recently [66]. This aims to provide seamless connectivity among "Carrier-grade Wi-Fi" and 3G/4G networks, as well as increased capacity. License-exempt bands alongside the licensed bands are aggregated employing the same CA techniques (subject to multi-band support of the Base Stations (BSs)) that are currently applied in licensed bands in the LTE-A. Thus, there is no need for significant modifications in the network infrastructure, implying a cost-effective approach from a mobile operator's point of view. On the other hand, due to the enhanced air link structure of LTE-A, provision of better performance is expected in the license-exempt bands compared to Wi-Fi networks with the same power level [66]. The small cells capable of operating in both licensed and the 5GHz license-exempt spectrum, can be identified as a primary use case of this access scheme.

Feasibility of LAA from UE perspective has been studied for unlicensed 5GHz in [67]. Regulatory requirements such as allowed transmit output power is investigated. With regards to implementation issues for aggregating carrier in unlicensed 5GHz band for inter-band CA, there exists some Radio Frequency (RF) architecture requirements and considerations including implementation complexity and performance. It is assumed one single front end filter in UE implementation to cover the entire 5GHz spectrum. In [68] RF requirements for UE both transmitter and receiver characteristics operating in Band 49 in 3.5GHz are reported. For the transmitter side, the maximum output power is specified in accordance with inter-band configurations with. The allowed Maximum Power Reduction (MPR), in-band emissions mask, out of band emissions mask are specified. For UE receiver side, characteristics such as reference sensitivity power level to support for inter-band CA operation, for serving cell, inter-band reference sensitivity, blocking of an unwanted interfering signal out-of-band blocking, and wideband intermodulation are discussed.

In the 3GPP specifications, LAA was finalised in LTE Rel. 13 for the downlink only. Rel-14, enhanced LAA (eLAA)adds uplink support as well [69], [70]. However, it is assumed that LTE-A is not supposed to operate as a standalone system on the 5GHz license-exempt bands, but the 5GHz band will be used in conjunction with the licensed bands in order to improve the system performance. The major requirement of deployment of LTE-U/LAA is to install the BS, which support multi-band operation (i.e., license-exempt bands in parallel with the licensed bands. Besides, although LTE-A in license-exempt bands can become a proper substitution for Wi-Fi networks in the future, in the existing networks, it should be ensured that the Wi-Fi users are protected from potential interference, when co-exist with LTE-A systems also operating in license-exempt bands [66], [71].

c. **Unlicensed Primary Shared Access:** In this access method, the bands are generally authorised so that all valid technologies are permitted to exploit them simultaneously. An example of this access method is co-existence of Digital European Cordless Telecommunications (DECT) operating in the 1880-1900MHz band as a PU via mobile service [25]. Under this access method there will be no costs for the license fee, however, technologies should implement spectrum sharing etiquette to prevent harmful interference.

To summarise, in the context of "spectrum sharing for mobile cellular networks", both licensed and unlicensed sharing schemes can be advantageous as both can provide additional capacity. In fact, spectrum sharing in mobile cellular networks can be deployed in a flexible manner to serve a wide range of applications and services with various QoS requirements in shared frequency bands. Unlicensed sharing schemes, with their opportunistic nature, facilitate the use of, e.g., licensed narrowband TVWSs, as well as license-exempt bands (e.g., 5.8GHz) for application with lower QoS requirements, such as emerging MTC and IoT services [72]. In contrast, licensed sharing schemes provide additional licensed spectrum (e.g., for mobile use) to fulfil strict QoS requirements of services such as Mobile BroadBand (MBB). However, the focus of this thesis is on licensed sharing schemes to facilitate utilisation of the licensed bands for cellular systems under "Licensed Access" classification (the shaded blocks in the taxonomy shown in Figure 2.1). The goal of this project was to come up with novel solutions via SS to make the most efficient utilisation of licensed sub-6 GHz bands. This range of frequency is much favorable (compared to above 6 GHz) due suitable propagation properties for mobile uses. The licensed schemes are focused because for mobile use, there is a need to convince the MNOs that the bands are made available on a guaranteed access basis (and not opportunistic). Thus, the sharing techniques under the taxonomy of "licensed-exempt access" (i.e., access to the shared bands in an opportunistic manner) remain out of scope.

Depending on the range of frequencies that become available through SS, both coverage and capacity gain can be achieved. Lower frequencies (e.g., 900MHz) can contribute to coverage improvement for mobile networks, whereas higher frequencies (e.g., 2.1GHz or even higher) where wider bandwidths are available can contribute to capacity and data rate enhancements. In this thesis where feasibility of REM for both LSA (2.3-2.2.4GHz) and IOSS (LTE-A bands) is investigated, mainly the capacity and data rate enhancements are assessed. However, the approach itself can be generalised to any bands (lower bands for coverage enhancements) and it is not band specific.

2.1.2 Key Spectrum Sharing Use Cases In Mobile Cellular Networks

As licensed spectrum is the most valuable asset of the MNOs, ownership/shared right of use of these bands enables them to deploy and efficiently manage their own network in such a way that guaranteed QoS, seamless mobility, and predictable performance can be offered to their users [66]. However, the MNOs currently own and operate on a limited range of licensed bands. Thus, licensed spectrum sharing can provide a promising way to reach this target. It is likely that the primary benefit of spectrum sharing will be the reduced costs compared to acquiring a license via auction. Thus, adapting LTE-A to operate in shared licensed spectrum (based on appropriate Service Level Agreements (SLAs)) can be considerably beneficial. Indeed, the key impact of licensed spectrum sharing is a robust and reliable capacity augmentation, which can be beneficial for various cellular network deployment scenarios such as; sub-urban/urban not-spot, urban/metropolitan hot-spot, and residential/indoor, etc. deployments, as follows:

1. **Sub-Urban/Urban Not-Spot Coverage Enhancement:** In order to provide coverage in not-spot scenarios (the areas where there is no coverage at all), in both sub-urban and urban areas, two solutions are currently available; investments for additional infrastructure in the respective areas (such as setting up new masts for sub-urban or small cells in urban scenarios). However, the level of additional investments by the MNOs targeting sub-urban "not-spot" scenarios to achieve 90% coverage for voice and text services, and 85% for 3G and 4G, can be significant and not cost-effective from business perspective [73]. The second solution is to ap-

ply for additional exclusive spectrum with desirable propagation properties. For instance, sub-1GHz bands such as 800-to-900MHz (which cover wide distances with low penetration losses) are preferable in both sub-urban and urban scenarios. To date, however, this range of spectrum has rarely been made available for mobile uses and is only available in small/low capacity chunks (from 5-to-10MHz) which fail to provide consistently throughputs, such as streaming video services. In this regard, spectrum sharing can play an important role to solve this issue. One potential type of sharing is "national roaming" (see Figure 2.2), where the MNOs manage to serve their users in not-spots. In the case that national roaming is not a desirable solution for the competitive MNOs, other types of sharing such as mutual renting and LSA-like approaches can prove beneficial. In this case, the MNOs can leverage their own existing infrastructure and access a wide range of desired bands in a shared manner, without the need for additional investments towards acquiring the exclusive license. Besides, the shared bands can be aggregated with exclusive bands to better accommodate the peaks in traffic demands.

2. **Urban Hot-Spots Capacity Improvement:** A wide range of shared bands that are made available through licensed sharing schemes, i.e., inter-operator spectrum sharing and LSA-like approaches, can be utilised by MNOs to handle traffic peaks in certain areas or during special events, where a more reliable and efficient technique rather than Wi-Fi traffic offloading, is required.

3. **Mass Deployment of Small Cells on Non-Cellular Bands:** As discussed in earlier, interference between tiers of cellular networks (i.e., macro, pico and femto cells), due to co-existence of tiers in the same bands is a concerning fact [14]. In the context of spectrum sharing, small cells (mainly indoor) with low transmission power BSs and low interference probability, can be suitable candidates to operate on shared bands which are made available through the LSA-like approaches, in higher frequency ranges. The bands can be assigned dedicatedly for small cell usage in order to alleviate the concern about small cells needing some portion of an MNOs'

exclusive licensed spectrum.

4. **Radio Access Technology (RAT)-Specific Bands Sharing:** Different 3GPP RATs such as; 2G, 3G, 4G/LTE, and LTE-A operate on varios frequency bands. Hence, spectrum sharing in multi-RAT scenarios can provide opportunities for the MNOs which do not own RAT-specific bands, and helps improve capacity and coverage expansion (Ofcom refers this type to as partial/operator-specific not-spot [74]).

5. **Capacity Enhancement Considering Frequency Division Duplex (FDD) and Time Division Duplex (TDD) Band Sharing:** The LTE TDD-FDD joint operation, was studied in 3GPP [75] with carrier aggregation (or instead, with dual connectivity feature). It facilitates simultaneous reception/transmission on FDD and TDD carrier to increase the frequency utilization efficiency. Moreover UE achieves higher throughput by simultaneously receiving and/or transmitting from both TDD and FDD carrier. Prerequisite, such as network architecture enhancement in order to facilitate FDD-TDD joint operation is expected under ideal backhaul assumption. In the context of IOSS, in an multi-MNO environment where the MNOs operate in FDD or TDD duplex modes co-exist, the TDD and/or FDD bands are shared. This sharing is managed (e.g., as of [76]) via a centralized software-defined networking based controller, which acts as a resource brokering entity with global resource/spectrum utilisation knowledge. The TDD and FDD bands are aggregated and jointly utilised the same regulations and considerations discussed in [75].

2.2 Research Challenges and Enabling Techniques

Learned from the discussion so far, considering the suitability of the bands for mobile services (namely the propagation characteristics of the band), potentially all the bands can be shared if they cannot be refarmed. The question that emerges at this point is; what are the requirements for the development and implementation of licensed spectrum sharing schemes? In order to achieve an efficient spectrum sharing target, Radio Resource Management (RRM) entities, micro-trading[1][77], and spectrum sharing enablers are invloved. RRM enablers identify suitable bands that can be used, based on technical criteria and their associated quality characteristics. The Micro-trading enables facilitate spectrum sharing based on economic criteria and cost by identifying the tradeable units in the temporal, spatial and frequency domains (e.g., lower time scales) [79]. Spectrum sharing enablers provide the means for accessing and releasing/evacuating the shared bands subject to rules and regulations (a combination of administrative and technical constraints) defined to protect the sharing players against potential interference. For instance, parameteres such as the maximum allowed transmit power, out-of-band transmitted power limits, and protection radii [80], etc., are taken into account. As a result, the practical deployment of licensed spectrum sharing, in a real-world environment, may well require dynamic coordination among sharing players to acquire real-time information about the availability of the shared bands in temporal-spatial domains, and therefore, the adoption of techniques which can capture these SOPs in a reliable manner, will be a key requirement.

In current Medium Access Control (MAC) protocols in cellular networks, where the MNOs operate on their own exclusive spectrum, a central entity, such as BS, handles different network functionalities comprising; spectrum allocation, intra-cell interference management within the coverage of its own cell, and inter-cell interference management between the neighbouring cells. The UE, however, may cooperate in a distributed manner and provide Channel State Information (CSI) back to the central controller (i.e., the BS) to assist the scheduler for efficient resource allocation. Besides, by the aid of ICIC techniques, through an interface such as X2, the adjacent BSs coordinate to avoid interference. In the context of spectrum sharing, e.g., IOSS, when an MNO operates on

[1]Spectrum trading is an important tool to open up opportunities for businesses to get access to desired spectrum dynamically and in a more flexible manners. Many models for spectrum trading have been studied by using different simulation tools such as; discrete-event simulation, agent-based computational economics [77]. These models usually require "long time to execute a trade, hence limiting the flexibility over short time scales". Spectrum micro-trading as a concept enables trading of spectrum on the micro-scale in three dimensions: the micro-spatial, micro-temporal, and micro-frequency scales with aid of technical cognitive tools such as sensing, dynamic bandwidth, spectrum aggregation, etc. The most important metrics are defined; market viability, spectrum utilization, channel quality [78].

shared spectrum, which belongs to the other MNO, such resource management functionalities are not sufficient, as each MNO is aware of spectrum allocation only within its own domain. The interference will be challenging when the participating MNOs simultaneously operate on shared spectrum in a particular area. In this respect, the MNOs need to be highly synchronised/coodinated in order to avoid interference. In the case of downlink, as well as when the MNOs' RANs are deployed in a collocated manner (100% geographical coverage overlap), or when they share same RAN, the synchronisation management can be straightfowarwd to some extent. However, the problem remains in the uplink (userswith different power levels). Besides, when the BSs are deployed in a non-collocated manner (different geographical locations), as the synchronisation requires fast/real-time information exchange among the BSs of different MNOs via the backhaul with reasonable capacity and speed. In fact, ICIC in multi-operator deployment scenarios require further investigations, as these techniques in the current LTE-A systems are only applicable for single operator scenarios, which might not be possible to extend such connection among BSs of two different MNOs [78].

Coordination between sharing players can be carried out through various methods which are realised as or "spectrum access" techniques/protocols. Functionalities and specifications of the existing (mostly considered) coordination protocols in the literature, which are applicable to inter-operator spectrum sharing and LSA schemes are explained below. The SOTA on the coordination protocols for IOSS and LSA, is discussed later in this Chapter, respectively. In general, coordination techniques can be categorised under centralised and decentralised classification, as follows, and their respective implementation challenges are summarised in Table 2.1.

2.2.1 Centralised-Based Coordination Protocols

In the centralised based coordination techniques, sharing players coordinate via a central entity, so that they do not directly interact with each other [25]. Centralised techniques, which have been applied so far, are discussed below:

Table 2.1: Advantages and shortcomings of coordination techniques for licensed spectrum sharing schemes

Coordination techniques		Advantages(+) and Shortcomings(-)
Centralised	Database driven (e.g., geo-location database) Spectrum broker/ Super resource scheduler	+ Provides accurate information regarding spectrum availability across the network. + Provides reliable interference protection for sharing players. + Can be an unbiased entity for fair spectrum allocation among sharing players. - Too complex for real-time spectrum opportunity detection. - Requires additional infrastructure such as backhaul for deployment. - Requires a third party to manage the sharing procedure. - Imposes excess signalling overhead to the network/participating systems. - Is vulnerable to jamming attacks.
Distributed	Spectrum sensing (e.g., energy detection)	+ Is capable for on-demand and real-time spectrum opportunity detection. + No additional infrastructure is required. + Only target UE is involved to perform sensing, thus, lower signalling is imposed to the network. - Is vulnerable to some issues such as hidden node, false alarm and detection. - Is not reliable for QoS sensitive services when sensing is performed by UE.
	Coordinated Beamforming	+ Simultaneous utilisation of spectrum by multiple service providers. + Increased spectrum utilisation efficiency. - Requires CSI sharing between sharing players. - Requires interface (such as backhaul, X2, etc.) between sharing players.
	Game-Theory based coordination	+ Low to no, information sharing between sharing players during sharing procedure. + Low to no overhead is imposed to the network. - Implementation complexities. - Low fairness guarantees between sharing players.

1. **Database-Driven Approaches:** Geo-location database is an indicative example of centralised coordination techniques. It can acquire, process, and store the geo-localised spectrum availability information of a service provider, which can be an MNO or an incumbent. In a robust but more complex type of geo-location database, the interference between users is calculated through the offline (non-real time) theoretical propagation models, which allow promising interference protection [58], [81]. This technique is widely applied in the case of TVWS [82] sharing, and also in the LSA reference system architecture.

2. **Centralised management entity via a third-party:** The method is applied considering; super resource scheduler [83], meta-operator [33], spectrum broker [84], and also shared Radio Network Controller (RNC) have been widely applied in the literature in the case of inter-operator spectrum sharing for reliable management of

spectrum sharing process. Each of these methods can follow specified policies such as; shared spectrum allocation based on Channel Quality Indicator (CQI) of the respective UEs, traffic correlation of the sharing players at a time, location of the UEs with respect to the BSs, etc.

The implementation of such centralised methods is subject to additional costs in terms of new required hardware/media. For instance, in the case of database-driven approaches, setting up a connectivity between the database and sharing players, are the least requirements. More specificfally, when sharing players have dynamically varying spectrum usage patterns, there is a need for frequent updates/queries of the centralised controller. For instance, in the case of mobile cellular networks with traffic diversity, the demand for shared spectrum dynamically varies over time/locations. This generates additional traffic in the network which results in the need for additional transmission resources to handle the messaging exchange. Signalling information can be transmitted using the wired backhaul, as the rising demand for mobile backhaul capacity is likely to be addressed through the use of fibre backhaul links and/or migration of fixed wireless links to higher frequencies, reducing congestion in the lower bands.

In addition, the time-scale of spectrum sharing can considerably affect the amount of signalling. For instance, in short-term sharing, due to the frequent resource requests, the signalling overhead is much higher than the mid-term and long-term sharing. In the mid- term sharing, operators agree to share their spectrum in a time scale of seconds to minutes in order to handle the peak hours. The long-term sharing, lasts from minutes to hours, reducing the system complexity, but allows for less flexibility and efficiency in terms of spectrum utilisation [85]. Thus, there is a trade-off between real-time spectrum sharing and overhead of centralised-based coordination techniques. In the new enhanced spectrum sharing frameworks. On the other hand, from a security point of view and preserving confidentiality of spectrum usage status, is a concern in centralised-based coordination techniques. However, there have been proposed some methods to reduce the concern of jam/malicious attack to have secure database in the literature such as in [86] (The security issues are out of scope of this thesis).

Generally speaking, the purely centralised-based coordination protocols are expected to be more suitable for static sharing schemes, where the spectrum usage status does not change on a real-time basis, or when the time scale of spectrum sharing is relatively long. The database-based coordination protocols become more complex and with rather high overhead to capture and store real-time spectrum availabilities, which makes them less favourable to be used in licensed spectrum sharing schemes (IOSS and LSA) with highly dynamic traffic demands. This technique, however, can be applied in the case of TVWSs sharing [87], [32], to deliver services with rather static/known spectrum usage pattern (e.g, some types of MTC services) and fixed TV transmitters/receivers' location.

2.2.2 Distributed-Based Coordination Protocols

Decentralised coordination: In the case of decentralised coordination, sharing players cooperate in a distributed manner. This is in contrast to the centralised coordination, where a central entity manages/monitors the sharing procedure. The decentralised techniques, which have been applied to so far, are discussed below:

1. **Spectrum Sensing:** By the aid of sensing techniques, devices (e.g., BS, UE, or any sensing capable device) can detect the presence of other devices operating on shared bands (or SOPs in general), prior to transmission, to avoid interference. A wide methods of sensing are available, ranging from; energy detection, feature detection of co-existence beacons [57], etc. Applying sensing techniques, the detection is performed on a real-time and dynamic manner, via the involved devices (i.e., any sensing capable device such as UEs, sensor nodes, etc.) only, thus other parts of the system/network are not required to be involved, resulting in lower overhead (in contrast to the centralised coordination techniques in which e.g., the BS, UE, a cental conroller, etc. are involved). However, reliable detection of the idle bands is subject to the system complexity and increased costs of enhanced sensing/measurement techniques [88]. Multiple threats affect the Physical Layer (PHY), such as malicious

node attack and in the MAC layer, the hidden node problem, and sub-optimal false alarm and detection probability issues [86]. Besides, the time duration which is required to perform sensing and detect the SOPs, leads to the reduction of the effective data transmission time (i.e., a trade-off between sensing time and data transmission time) [57], [89]–[91].

The currently available distributed sensing techniques are not typically considered as highly reliable methods [88], to be applied for the spectrum sharing. This problem will be concerned more specifically in the cases where the sharing players are different in nature and have strict interference avoidance regulations (e.g., LSA). In [92], a comparison of advanced sensing techniques is carried out, indicating that, under realistic channel models and assumptions, a probability of detection of 90% is achievable at SNR roughly -10 dB, which falls near the desired targets, e.g., those set in [93] (-12dB for detection of Wireless Mics). Although the performance of other sensing techniques such as; feature detection, covariance, matched filter-based techniques may be superior, the implementation and computational complexity remain prohibitive [57], [94]. As a result, the distributed coordination approaches that are purely based on sensing techniques are more suitable for Wi-Fi co-existence cases, where QoS requirements are not strict [43], [58], [88].

2. **Coordinated Beamforming:** Enables the mobile cellular networks to adjust size and position of the cells to better serve users. This is achieved by flexibly modifying the phase and amplitude of the signals to shape and steer the direction of the radiated beam vertically and horizontally to create constructive or destructive interference. Constructive interference is used to amplify the beam in a given direction, while destructive interference is used to focus the beam, enabling it to be steered precisely [95]. In the context of spectrum sharing, beamforming techniques facilitate co-existance of multi-technology deployments. However, the coordinated beamforming is subject to the sharing of CSI and even of user data between the sharing players in order to avoid inter-system interference. This is realised as the main concern in

real-world deployments of this technique in spectrum sharing (mainly IOSS) [96].

3. **Game Theory (GT) Based Coordination:** GT is a well-defined technique for studying distributed decision-making in multi-user systems. Game-theoretic frameworks have been applied to the problems such as power control, spectrum allocation, call admission control, and routing. In the case of co-existence of multiple service providers, the resource/spectrum sharing problem can also be investigated from a game theoretic perspective. Depending on whether players collaborate or not, a game can be cooperative or non-cooperative. Without coordination among users/systems, the existence of stable outcomes is analysed through the so-called Nash Equilibria (NE) [97], [98]. To achieve better payoffs, cooperation between users may be carried out. Subject to sharing some information, players can determine whether there are potentially extra utilities for everyone if they cooperate. If there are such extra utilities, players may bargain Nash Bargaining (NB) with each other to decide how to share the information. The NB solution, in fact, is a specific game which depends on the manner of cooperation [59], and [99]. However, the success of GT-based solutions in the case of resource/spectrum sharing and allocation in mobile communication systems, requires robust solutions to the open challenges such as implementation complexities, uniqueness complexities, efficiency and fairness, etc [100].

From the discussion above, it can be concluded that each coordination technique is applicable to the scenarios characterised by different demands. The centralised based techniques, are simpler to be controlled, and provide more reliable and fair allocation of spectrum. However, there is a need for additional network infrastructure, and subject to considerable amount of signalling overhead for coordination between sharing contributors, especially the ones with dynamic varying traffic load, and dynamic spectrum usage. Besides, the latency in such schemes matters, when the real-time traffic is transmitted, as well as when the time-scale of sharing is low, due to the fact that coordination with the central entity requires additional time. In the distributed based techniques, on the other hand, the adoption of an efficient, accurate and reliable technique is a challenge.

Current generation of spectrum sensing techniques are unlikely to be suitable enablers for licensed spectrum sharing schemes. The MNOs, with strict interference protection requirements that expect any probable interference originates from their own network, are unlikely to employ and rely on such coordination techniques solely. This problem will be more concerning in the future cellular systems, where services such as MTC, share the licensed bands with cellular systems. Besides, coordinated beamforming techniques are subject to exchange of information (e.g., spectrum usage information and sometimes user data such as CSI) between the competitive sharing players, which is less favourable. In fact, the spectrum sharing schemes need to be evaluated under realistic assumptions (whether sharing of information is viable in real world), in order to establish the performance gains, and identify potential business level enhancements, prior to the deployment, so that they incentive the sharing players to contribute in spectrum sharing. Therefore, to ensure that operation over shared bands is as robust and reliable as typical (non-shared) licensed communication, there is a need for the adoption of coordination technique(s) that is capable of near real-time monitoring of the environment in a distributed manner in conjunction with reliable centralised decision-making technique(s).

2.3 Deployment Scenarios

In this Section, licensed spectrum sharing scenarios are introduced. Based on the discussion provided in Section 2.1, it is evident that licensed spectrum sharing for the mobile cellular networks is currently plausible through two different schemes (IOSS, and LSA). Through each scheme, different licensed spectrum bands (in the case of IOSS, the LTE-A bands and in the case of LSA 2.3-2.4GHz) can be made available in a shared basis. Besides, each scheme involves sharing players of various types, which introduces different requirements and challenges that should be investigated prior to the deployment. Hence, the terms homogeneous and heterogeneous are applied in this thesis, based on the sharing players' nature, and consequently a classification of the licensed sharing schemes based on the characteristics of sharing players is introduced as follows (depicted in Figure 2.2). It is worth to note that, as the focus of this thesis is in mobile cellular networks, the scenarios in which at least one sharing player is an MNO, are addressed. However, this taxonomy can be extended and applied to the spectrum sharing scenarios between non-mobile carrier-grade service providers that may emerge in the future.

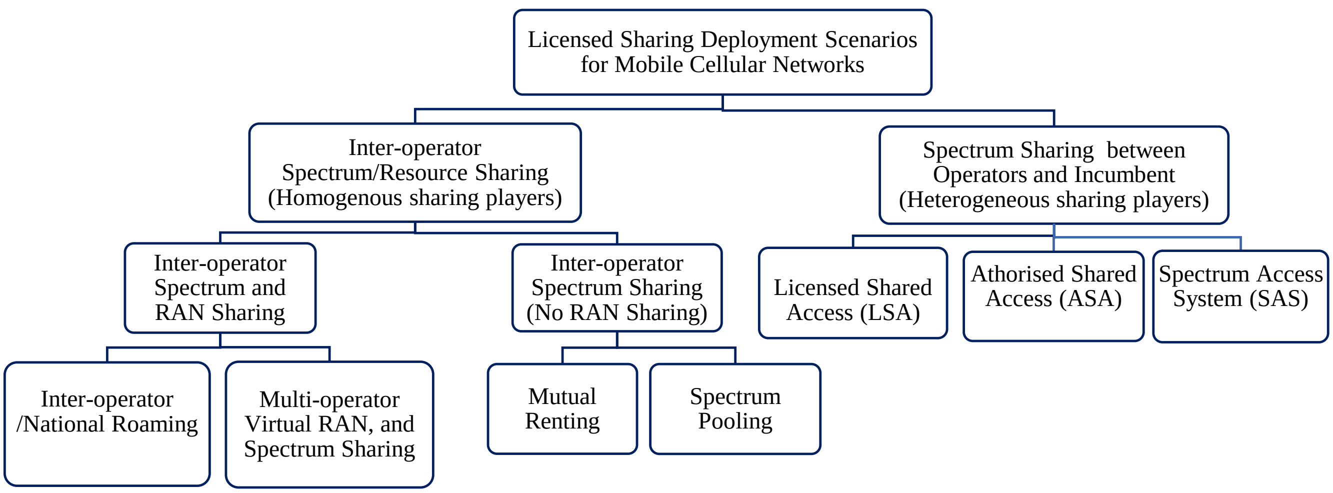


Figure 2.2: Taxonomy of licensed spectrum sharing deployment scenarios.

2.3.1 Homogeneous Sharing Players

This classification refers to the sharing players of the same nature, where they employ similar network infrastructures, deliver similar types of services to the users, and therefore, have the same system/performance requirements and sensitivity. IOSS among two or multiple MNOs can be classified under this category. Obviously, the bands that are made available through these sharing schemes are the ones which have been already allocated to the MNOs. It should to be noted that, spectrum sharing between the MNOs itself encompasses various types. Multiple scenarios of inter-operator spectrum/resource sharing are presented in Figure 2.2 (the references shown in the figure relate to the SOTA approches which are dicussed later in this Chapter). In the following sub-sections, in terms of MNOs' RAN deployment, two different deployment scenarios are considered where the MNOs are either collocated, having the same cell coverage or non-collocated, covering different areas (where cells of different MNOs might partially overlap) [101].

1. **Inter-Operator *Spectrum* and *RAN Sharing***

   This sharing scenario is categorised as: a. Inter-Operator/National Roaming where the MNOs deploy exclusive RAN in either collocated or non-collocated topologies, and b. Common Spectrum and RAN Sharing when two different MNOs cover the same geographical area.

   a. **Inter-Operator/National Roaming:**

      The possibility for a UE to operate in a network other than its own home network is referred to as roaming (also termed inter-operator handover). This is typically performed by the UE, which measures the signal strength of the pilot/reference signals of the neighbouring BSs and consequently will be connected to the BS with the strongest pilot/reference signal. The term national roaming implies that multiple MNOs, owning exclusive spectrum, RANs, and CN nodes, provide coverage in different parts of a country but together can provide coverage of the entire country. National roaming can be considered as both RAN and spectrum sharing in non-collocated deployment scenaris, which is carried out based on agreements among the MNOs. In the case of national roaming, interference and mobility management of the involved UEs are straightforward and less challenging, as the UEs/BSs perform handover to the coverage area of the target MNO, and thus, the target MNO is responsible for resource allocation and management of the UEs [102]. In the 3GPP specifications [102] inter-operator/national roaming has been studied.

      In such scenarios, mainly asymmetric traffic fluctuations among the MNOs are taken into account to determine SOPs for the purpose of sharing. In Figure 2.3, network topology, as well as information exchange procedure of this scenario are

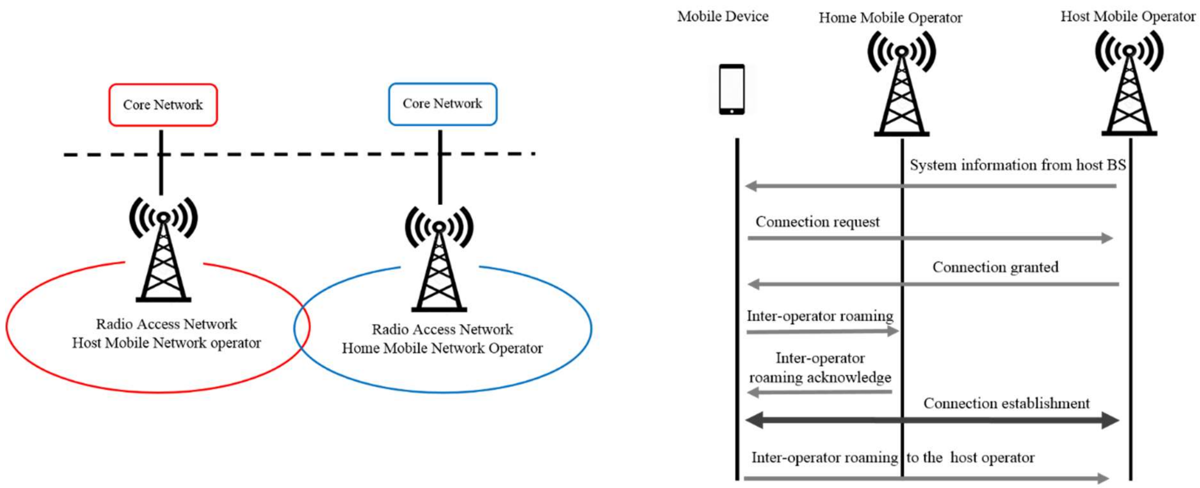


Figure 2.3: Inter-operator/National Roaming (a) Network topology, (b) Connection setup flow [102], [103]

shown.

b. Multi-operator virtual RAN, and spectrum sharing (common spectrum and RAN sharing):

Due to the heterogeneity of the sharing parties, there is an opportunity of network sharing among the MNOs. Network resources (infrastructure) such as Core Network (CN) node, and RAN can be shared [102]. The reference/high level network topology as of [102] is depicted in Figure 2.4.

Network sharing between the MNOs is a well-recognised form of network-related cost optimisations, as it allows a significant Capital Expenditures (CAPEX) and some Operational Expenditure (OPEX) reductions particularly in low traffic areas as depicted in Figure 2.5 [104]. It is expected that the operators can save considerable amounts of money through RAN sharing over a 5-year period. It is also generally agreed that RAN sharing can lead to a faster roll-out of new technologies, e.g., LTE/LTE-A, whilst reducing costs, particularly for the green-field operators [101], [105].

Network sharing can take many forms, ranging from passive sharing up to active

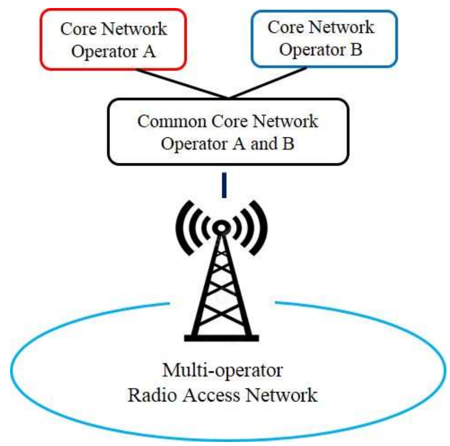


Figure 2.4: Multi-operator RAN topology (common spectrum and RANsharing) [102]

sharing, and is deployed subject to each MNO's policy and legislation in each country. Passive sharing refers to the sharing of non-active elements of the network, i.e., the nodes/elements, which do not participate in the transmission of signals, such as physical site (the most common form of passive sharing practiced by the MNOs since the introduction of 3G systems), and can include sharing of mast, cooling equipment and power supply.

On the other hand, active sharing comprises active network elements, such as BS, baseband unit, and radio remote head [104], [106]. It can also involve fully integrated models such as, Multi Operator Radio Access Network (MORAN), and Multi Operator Core Network (MOCN). In MORAN the RAN, and gateway CN, are shared. In MOCN both RAN and some parts of CN node are shared. The adopted models, however, should be flexible enough to enable both sharing parties to follow their respective business strategies. The models can be applied to different RATs and geographical areas, potentially based on the traffic density. A cost-optimised strategy will involve multiple partners and require new and flexible ways of sharing infrastructure. As an example, EE operator in the UK has implemented a pro-active approach to network sharing for a long time. More details of the architecture and functional requirements associated with these

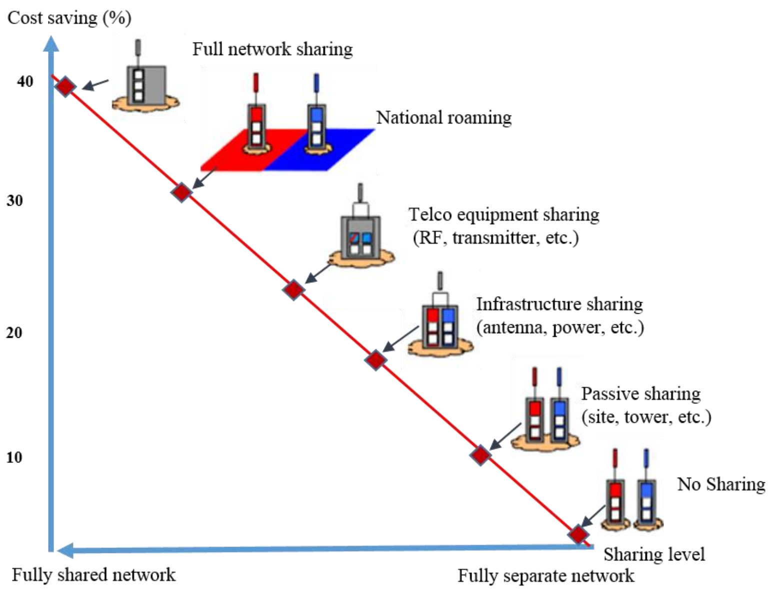


Figure 2.5: Network sharing models and corresponding cost saving gains [104]

models can be found in [23]. In [107], sharing of both spectrum and network infrastructure is considered to investigate coverage and data rate trade-offs of each possible sharing scenario.

The virtualised RAN and spectrum sharing, that enables the deployment of virtualisation in cellular networks with subsequent support for Mobile Virtual Network Operator (MVNO) has been studied in [104], [108].

From the regulatory body's point of view, inter-operator resource sharing can have considerable impacts on efficient resource utilisation. The regulators enacted the telecommunications services wholesale regulation, to let MVNOs enter the mobile telecommunications service market [109]. Due to MVNOs entry, the mobile telecommunication service market was expected to become more competitive. In order to improve competition in the market, the regulator has developed and applied relevant policies for MVNO, i.e., to reduce the rate of wholesale prices paid by the MVNOs to their mobile network suppliers and to exempt MVNOs from spectrum fee. According to the regulations [29], [109], a new entrant can launch its service only with 25%

network coverage of the country and can request to share existing MNO's resources. For the host MNO, it is mandatory to share the resource by the regulation for up to 5 years. Within this 5-year, a new entrant has the responsibility to have its network provide 95% coverage. The utilisation of other MNO's network resources will lead to reduced initial investments for the new entrants, and hence, lowered risk to enter a market.

Overall, The inter-operator spectrum and RAN sharing approach has been implemented in many countries in the context of international roaming, however, inter-operator spectrum and RAN sharing approaches in national level has not been practically used so far. MNOs provide services to the subscribers in a very competitive market. Thus, for spectrum sharing between operators, the needs for spectrum sharing accompanied with mature relevant technology.

2. Inter-Operator *Spectrum* Sharing

In this type of sharing, only spectrum as a resource is shared among the MNOs, which can be performed in both in collocated and non-collocated network deployments. In some collocated scenarios, however, the MNOs can also share the cell site, tower, etc., (passive infrastructure sharing), and is classified as; a. Mutual Renting, and b. Spectrum Pooling, where both conform to the access modes in the individual authorisation (Figure 2.1, and Figure 2.2) classification.

a. Mutual renting: The concept of mutual renting was explained in Section 2.1. The involved MNOs can be termed home and host MNOs (sharing can be bidirectional or unidirectional). The main concern, in this type, is to find an efficient and reliable method for the UEs of home MNO to detect and access the free SOPs while protection of the UEs of the host MNO from interference is taken into acconut. In this respect, when the BSs of the involved MNOs are collocated, interference management is rather straightforward, as due to the binary nature of spectrum access (either the host or home MNO can utilise the spectrum at the same time/location). In the non-collocated case, however, the interference occurs

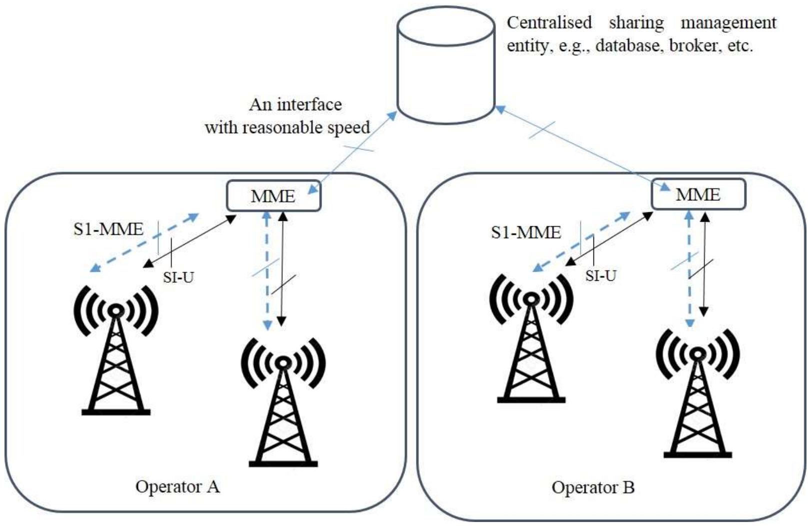


Figure 2.6: Inter-operator coordinated mutual renting via central third-party entity [33]

when the BS of the home MNO negotiates with the adjacent BS of the host MNO regarding the SOPs and, if permitted, allows its users to access the shared bands. In that case, UEs moving across the cell may cause interference to those UEs of the host MNO who are using the same bands in adjacent cells, risking distraction of the frequency re-use pattern of the host MNO. Hence, the BS belonging to the home MNO might need to coordinate with multiple adjacent BSs of the host MNO to avoid interference, which is not the ideal solution [33], [110]. Therefore, this sharing type entails adoption of efficient coordination protocols to capture spectrum availabilities in an efficient and reliable manner. Below, some of the relevant available approaches are discussed. An example of network architecture for the deployment of coordinated mutual renting between MNOs is depicted in Figure 2.6.

b. Spectrum pooling: The concept of spectrum pooling was explained in Section 2.1. This sharing method can be deployed in either a cooperative (real-time coordination among the MNOs) or non-cooperative (non-real time coordination among the MNOs) manner. Due to the simultaneous utilisation of the shared bands by the MNOs, the probability of interference can be relatively high. There-

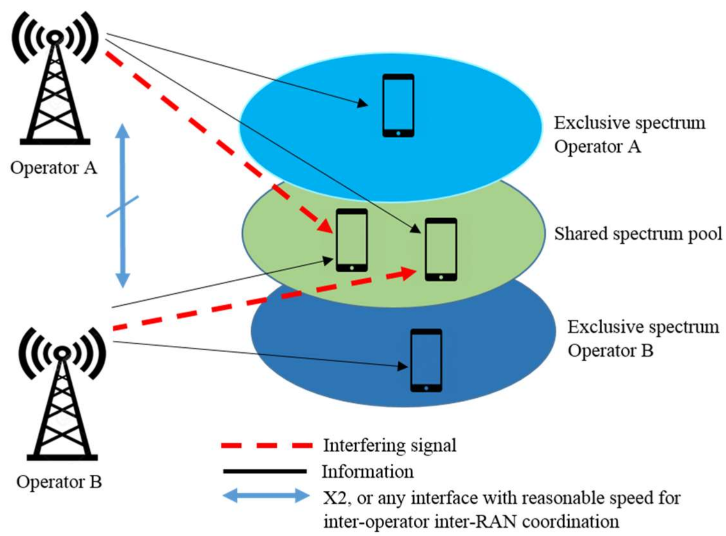


Figure 2.7: Multiple operators' transmission on a shared spectrum pool through beamforming techniques [111]

fore, either a tolerable level of interference must be agreed among the MNOs prior to utilisation of shared bands, or a robust coordination protocol is required, to manage sharing procedure. A vast majority of the techniques related to this type of sharing have been proposed, which some of them discussed earlier in this Chapter. This scenario, in general, is distinguished by the network topology deployment, the policy of shared spectrum allocation, and applied coordination technique. An exemplary type of this sharing method is depicted in Figure 2.7.

2.3.2 Heterogeneous Sharing Players

Refers to spectrum sharing among non-mobile service provider(s) (could be a governmental/commercial incumbent such as military and also Program Making and Special Events[1] (PMSE) [114], and mobile cellular networks where the sharing parties of different nature. The LSA/ASA and SAS frameworks fall in this category as shown in Figure 2.3. In the LSA framework, the incumbent agrees to share part of its exclusive

[1]PMSE services comprise a range of wireless services, such as wireless cameras and microphones used in live theatre/concert/sports events and outside broadcasts. A wide variety of spectrum bands are allocated for PMSE use such as 2200-2290 MHz, 3400-3410 MHz (in the UK) [112], [113].

band with one or multiple MNOs, referred to as LSA licensees. The framework was introduced with the aim of offering promising opportunities for the capacity and bandwidth expansion in cellular systems [44]. The bands which have been recently emerged (currently target 2.3-2.4GHz in EU and 3.5GHz in the U.S.) are preferable for use by cellular systems.

Similarly, to the IOSS schemes, in the LSA framework the sharing process involves adoption of coordination techniques with accurate and strict interference management policies. This is mainly as a result of severe sensitivity/vulnerability of the incumbents (such as radar systems) to the interference may incur by cellular systems in a way that any performance degradation of an incumbent is likely to decrease the probability that they would invest in shared spectrum. In this respect, in the current deployments of LSA, the focus is principally on the database (namely Geolocation database) driven approaches (known as LSA repository). The database stores the information regarding the shared spectrum availability/usage of the incumbent's network and can be setup and managed by the incumbents or the respective NRA. In the mobile cellular network side, an additional management entity referred to as LSA controller, has been introduced to interact with the LSA repository through a reliable interface [115]. The LSA controller is responsible for handling the resource request/evacuation procedure among the Operation, Administration and Management (OAM)) section in the mobile networks, and the LSA repository [44], [114]. The reference system architecture of LSA framework is illustrated in Figure 2.8.

Some factors which must be considered prior to the deployment of LSA are pointed out below:

- **Traffic steering:** As discussed earlier in this Chapter, the LSA bands should be evacuated, by the time they are requested by the respective incumbent. Thus, in that case, the MNO will have to serve the UEs over its own exclusive bands. The band evacuation phase becomes concerning more specifically if the BSs are not capable of operating in multi-bands (assuming the BSs are capable of CA , e.g.,

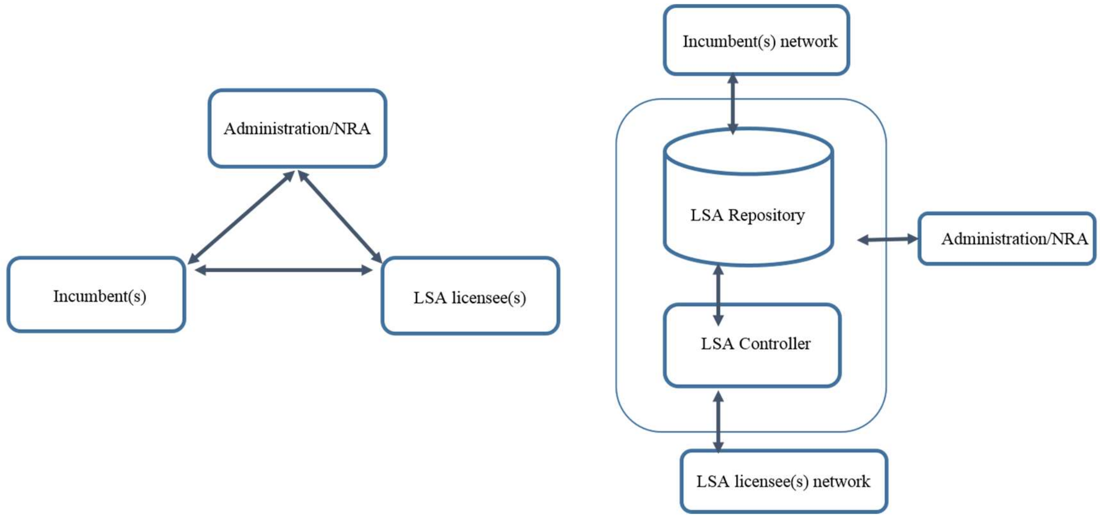


Figure 2.8: High level LSA reference architecture; (a) administrative, and (b) functional implementation [44]

inter-band non-contiguous CA, it makes sense that BSs are capable of multi-band support). Any time the bands are requested by the incumbent, the BS should cease operating and a shutdown process must be carried out. The MNO needs to perform traffic steering and handover to serve the UEs through adjacent BSs, which are operating in typical exclusive bands [116]. In the case that the target BSs are heavily loaded (Or when the exclusive bands are all utilised) and are not able to accommodate these UEs right away, queuing time will be increased or even connection dropping may occur. Thus, this problem needs to be further considered when the LSA bands are dynamically reclaimed by the incumbent (e.g., the case of PMSE), in contrast to the case when the incumbent (e.g., the military) shares the bands in reasonable time scales such as months, years or in remote regions [114]. According to [116], the band evacuation phase in LSA requires appropriates optimisations that determine how fast parameters such as the antenna direction, frequency band or even power level, can be altered. Applying LSA bands for indoor scenarios with low power BSs may seem to be a reasonable solution for this problem [117].

- **Support for scheduling/CA of non-contiguous bands:** As there is no guarantee that the assigned LSA spectrum across various MNOs will be contiguous with the spectrum already owned by a particular MNO, there is a need that both BS and the UEs to be capable of supporting non-contiguous CA [118].

- **Power control:** Based on the incumbent's interference protection requirements, different maximum allowed power levels are defined and agreed with the LSA licensee, more especially when the bands are used in macro cells with high transmission power and outdoor wide area coverage. Thus, exclusion zones for incumbents in terms of geographic and/or frequency separation must be strictly defined and agreed [44], [114], [119].

- **Signalling:** Additional signalling introduced to the network of both sharing players is an inevitable part of this framework the same as other SS types. The LSA sharing procedure comprising; spectrum request, allocation, and evacuation between an MNO and incumbent, introduces an additional overhead to the system. The degree of signalling overhead will be considerably increased in the case of near real-time/on-demand sharing. In the case of the long distance between the MNO and the incumbent's network, the coordination requires an interface/backhaul with reasonable speed/capacity. In this regard, an efficient interface between the LSA controller and the MNOs network, along with the appropriate network architecture (the enhanced reference architecture) should be applied in order to reduce both the signalling and the duration of coordination procedure (i.e., from the resource request to resource supply).

  Moreover, the MNOs in order to get the most benefit out of LSA spectrum with minimum latency (due to the information exchange), can have the LSA controller located within the LTE-A infrastructure (e.g., BSs' site) and connect with their CN node through an entity that has a direct connection to either the Serving Gateway (SG) or the Mobile Management Entities (MME) over an interface such as S1 connection.

From the mobile cellular network perspective, in the LTE specifications from Rel. 11 onwards, the required signalling implementation of LSA is supported in MAC and PHY on both UE and BS sides. The LTE/LTE-A signalling (control plane delay aspects of LSA), and RRM mechanisms that can be reused includes; Remote Radio Heads (RRHs) or small cells, CA, and Dual Connectivity (DC) [120], [121]. Besides, in some works such as [122] an "LSA management unit" is suggested to be deployed, to have control over the entire network of an MNO for faster decision making procedure. This unit is expected to collect some level of information such as traffic status, location, transmit power of a cell and also the direction, height and angle of antenna (of the BSs) which also helps interference mitigation between incumbent and MNO, and therefore to have more efficient utilisation of the LSA bands.

- **SOP availabilities:** The LSA framework in contrast to the IOSS schemes in which the traffic load of MNOs dynamically varies, and hence, the availability of SOPs potentially changes in a dynamic manner, is very much dependent on the type of incumbent. The bands can become available for rather longer time intervals or wider geographical areas. As an example, military (as a governmental incumbent) can introduce specific exclusion zones (temporal and/or geographical restriction) on a long-term basis. On the other hand, in more dynamic cases, such as radar or PMSE incumbents (where the spectrum usage pattern dynamically varies in temporal/spatial dimensions), there is a need for more interactions between the sharing players. Spectrum sensing can be added as a complementary method to make the database (LSA repository) more accurate and dynamic incorporating the additional information that sensing provides. Therefore, further research is required in order to explore and develop the hybrid and cost-effective approaches, in which both geolocation databases and sensing techniques are jointly applied [123].

- **Inter-RAT interference:** The co-existance of cellular systems operating on

LSA bands, i.e., 2.3-2.4GHz, with Wi-Fi (in the adjacent bands 2.5GHz) should be considered which raises the concern of inter-service interference. In order to mitigate this issue among different services/RATs in adjacent bands, guard bands, known as block-edge masks [124], of appropriate size must be specified. The size of the masks, however, may vary depending on the transmission power limits (tolerable interference threshold) required by different types of services, as well as the number of MNOs/MVNOs participating in sharing.

2.4 Deployment Requirements From Business/Regulatory Point of View

It is reasonable to expect that the deployment of spectrum sharing introduces economic and business concerns to the sharing players. This can comprise the costs of additional infrastructure, probable required modifications of the existing systems to support and manage the sharing procedure [72], license fees and restriction of competition among MNOs in the market, etc. Thus, apart from the necessary technical analysis, business issues associated with spectrum sharing also have to be investigated whether the sharing is worth the investment to achieve the claimed benefits. In fact, there is a trade-off between the costs and benefits of spectrum sharing. The main known business concerns associated with the deployment are briefly discussed below.

- **Additional Infrastructure:** As discussed earlier, depending on each sharing scenario, the required level of coordination and also the type of information exchange among sharing players will vary. The information, which can range from slowly varying (static) data (such as average propagation conditions), up to real-time (dynamically varying) data (such as CSI or traffic load of the cell), have to be transferred between networks/systems through a specific media such as wired backhaul, X2 interface, etc. The inter-site control data rate has been estimated to be approximately 96Mb/s in the case of negotiation among two MNOs, whereas considering 3-sectors/cells, the practical backhaul rate for one cell in a dense urban scenario and also one site are almost 100Mb/s and 300Mb/s respectively [78]. This shows that the amount of control information which is required to be exchanged is large and is almost equal to the effective backhaul capacity of one cell. Thus, it can be concluded that, a static spectrum sharing scheme brings lower costs in terms of operational complexities and the corresponding additional investments. However, it degrades the overall goal of spectrum sharing, which is the most efficient use of spectrum. A more dynamic type of spectrum sharing, in contrast, has higher operational complexities resulting in additional investments to manage the service-level guarantees. The concept of infrastructure sharing [108] (discussed earlier), is expected to reduce these costs considerably.

Besides, obviously the LSA framework provides revenue for both incumbent and MNO. However, the initial deployment, maintenance, and management of such framework introduce additional costs to both sharing players. From the MNO's perspective, apart from the additional functional block(s) (i.e., the LSA controller) on top of the cellular network architecture and the need for interfaces (e.g., wired/wireless backhaul or S1 link), the need for reconfigurable BSs and UEs have to be considered. In that sense, appropriate radio frequency electronics, capable of communicating over wide range of frequencies will be required. On the other hand, from the incumbent's point of view, the cost of setup and management of a database, as well as the interfaces, such as backhaul connectivity, should be taken into account. Since the required architecture in LSA is still an open topic [44] the tasks of different management units may also be defined in different trends. In this respect, the question that comes up is; which one of the sharing parties is responsible for the upcoming costs of administration and management of the sharing procedure [48].

Currently, it has not been specified whether the LSA is going to be deployed on a voluntary basis, or if incumbents will be obliged by the respective NRAs for the deployment. In general, an appropriate business model is required in order to determine the costs and also specify the available technological solutions that can be used to get the best possible revenue out of LSA. This requires potential synergies among different incumbents and MNOs.

- **Multi-band Operational Capabilities:** The support of new frequency bands requires software and hardware modifications in both transmitters and receivers in UE and BS which incurs additional cost in the market. The BSs require further enhancements in order to be able to support increased spectrum bandwidth, increased number of end users, additional processing power, and enhanced backbone capacity. The wider spectrum bandwidth requires more processing power, especially for the PHY layer processing and the complexity is known to be increased linearly with the spectrum size [78]. In LTE-A specifications where CA is supported in both uplink and downlink, some part of the modifications are already applied to support for multi-band operation.

- **Uncertainty and Business Risk:** Established MNOs and incumbents may realise spectrum sharing as a threat in the market. The need for information sharing and lack of efficient and standardised coordination techniques create uncertainty in the market. Besides, the possibility of greedy re-use of shared bands is considered as another concern which makes spectrum sharing less attractive for them to proceed with the investments. However, this has to be noted that, spectrum sharing is considered as a complementary method, and is not intended to be a substitution for exclusive spectrum allocation. Moreover, in the case of IOSS, the MNOs may share the spectrum bilaterally, so that it does not affect the competition for the spectrum in the market. Taking into account also the fact that the business goals of sharing players are not always equal to the goals of NRAs.

  Moreover, in order to reduce threats in the market, there must be a guarantee that a sharing request only occurs in the case of spectrum shortage and does not lead to permanent utilisation of the shared spectrum. A number of business models have nonetheless been proposed and discussed in technological, regulatory and business aspects [44], [46], [19], [125], [126].

- **Licensing Policy:** The cost of license for guaranteed access to the shared licensed spectrum is another consideration of the sharing players. In the case of spectrum sharing, the license fee will be lower than the cost of an auction-based license (conventional trend for spectrum allocation) or via trading (spectrum is assigned to a new user who needs it) [125]. There have been proposed varieties of trading schemes for the pricing such as channel-quality based price, game-theoretic based (such as NE), and also demand-supply model in which the shared bands are assigned to the highest bidders [127], and spectrum leasing [64]. However, more reasonable pricing policies are required to incentive sharing players to participate in spectrum sharing.

It is worth to note that, the main focus of this thesis is on; frameworks, mechanisms, algorithms, assumptions, associated challenges, advantages, implementation issues, and deployment scenarios, from a technical perspective. Thus, the studies pertaining to the business aspects such as; "auction mode", "merchant mode", investigation of budget limits, costs, and savings in spectrum sharing, are not discussed in detail in this thesis. Such issues are likely to be determined by the NRAs and are variable in each country. More information on analysis of the economic and business aspects can be found in [48], [127], [128]. Besides, the "game theory" (GT) based appraches which have been broadly applied for the purpose of spectrum pricing policies as a function of interference, investigation of budget limits, costs, and savings in spectrum sharing are out of scope of this thesis. More detailed information can be found in [95], [98], [99], [129]–[132] .

2.5 State-of-The-Art Proposed Approaches

In this section, the SOTA proposed SS approaches underlying: licensing regimes highlighted in Figure 2.1. (shaded in blue), the sharing scenarios introduced in Section 2.3 (shown in Figure 2.2.), along with the incorporated coordination techniques (pointed out in Section 2.2) are discussed to investigate the achieved gains with respect to the corresponding deployment challenges/requirements. The scope of this thesis is limited to the IOSS, and the LSA framework.

2.5.1 Inter-Operator Spectrum Sharing (IOSS)

1. Inter-operator/National Roaming

In [33], inter-operator roaming is investigated, based on a pre-agreement between the MNOs, and assuming the instantaneous traffic loads are not entirely correlated. As discussed earlier in inter-operator roaming each MNO controls over its allocated spectrum, thus, there is no risk of co-channel interference due to roaming (example of a conservative approach). Besides, there is no significant modification requirement in the cellular networks architecture. This sharing scenario, as a very primitive type, has been broadly considered in the literature [29], and seems to be a feasible solution for coverage improvement in the areas that an MNO does not own network infrastructure. The packet drop rate of UEs is shown to be reduced as a result of sharing with respect to baseline LTE-A when no sharing is applied. However, the gain (in terms of capacity) will be very much dependent on the traffic correlation between the MNOs. Moreover, the need for broadcasting MNO specific information (such as reference signals) across the network, is subject to agreement between the MNOs.

In a most recent work [133], a roaming-based sharing framework is proposed, in which, the MNOs dynamically monitor their load and spectral needs, applying "Q-learning algorithm" which enables the BS to dynamically determine its load-based spectral needs. If a BS/cell is identified as overloaded, it offloads its UEs to any BS that offers the highest SINR (regardless if the BS belongs to the host MNO or home MNO). It is stated that, through this policy the achieved gain from SS does not depend on the traffic correlation of the MNOs (in contrast to [33]), and enhances UE's Quality of Experience (QoE)(the QoE is defined here as the ratio of number of Resource Blocks (RBs) allocated to the UE, to the number of RBs requested by the UE), as well as improved spectrum utilisation efficiency (as UE with low SINR requires more spectrum resulting in poor spectrum utilisation efficiency). This approach is beneficial in the case of non-collocated deployment of BSs where they have partial/no coverage overlaps. However, for the multi-MNO deployment of BSs, with 100% coverage overlap is not discussed/shown. This is an important point to show how much gain can be achieved through this approach that can be applied in future generation of MVNOs and virtualised multi-MNO RANs.

2. Multi-operator virtual RAN, and spectrum sharing

In [33], a multi-MNO virtualised capable RAN is considered. The spectrum is shared between the MNOs managed by a centralised controller in a network level which monitors the sharing procedure and coordinates with the MME of the two MNOs. An MNO is overloaded in a specific cell and sends a request to the centralised entity for shared spectrum. The performance improvement is shown in terms of reduced packet drop probability in virtualised networks compared to the roaming-based, as well as the spectrum-only sharing. In this approach, it is concluded that, shared RAN can be highly beneficial compared to the case of spectrum sharing (which is addressed below), due to the required real-time interaction and information exchange among the displaced RANs of different MNOs for ICIC purpose and the required interface such as X2. However, it is also stated that, it imposes additional costs in the system to support virtualisation capabilities, such as software/hardware reconfigurable radio frequency frontends. In [105], proof-of-concept and prototype design and further studies and investigations are discussed for virtualisation.

It is observed that no coordination technique from Table 2.1 is incorporated/required in these approaches. In the next two sharing scenarios, the coordination techniques are applied, thus, to ease following up the contents, the approaches are categorised by the type of coordination technique as well.

3. Mutual Renting

Centralised Management Entity Based

In [33], a central third-party entity is assumed as a message exchange interface to manage the coordination between the MNOs regarding the bandwidth is being shared upon demand, to avoid risk of interference. The MNOs are termed "supply" and "demand" MNO respectively. It is pointed out SS becomes challenging and difficult to achieve gain when multi-cell layout (more realistic network deployment scenario) is considered between two independently deployed MNOs. In the multi-cell network layout with frequency re-use one, all the cells/sectors belonging to the supply MNO which surround (i.e., overlap partially or entirely) the cell/sector belonging to the demand MNO, must stop operating on the shared spectrum to avoid interference (when demand cell/sector request for shared spectrum, as the frequency reuse is one all the cells/sectors of the supply MNO operate in the same spectrum bands, and there is no geographical knowledge of spectrum utilisation in adjacent/overlapped cells/sectors all the overlapped cells/sectors have to have/provide/release the same set of spectrum to avoid interference).

It is stated that; this means multiple cells/sectors share spectrum with one demand cell/sector, which results in limited-to-no spectrum sharing gain (the authors are pointing to this as a problem/challenge in SS, t(hat based on this approach they propose) it is almost unlikely to find same set of free spectrum in all adjacent/overlapped cells). Considering this method of coordination, the authors conclude the inter-operator roaming is more efficient compared to the solid *spectrum* sharing. Besides, the need for additional resource such as backhaul (or additional spectrum) as an interface to exchange the messaging information is considered as concern in this approach.

In [134], the authors stress the necessity of coordination between the MNOs, when they share part of their bandwidth. It is stated that; assuming the MNO specific reference signals are not shared between the MNOs, it cannot be identified which part of the shared bandwidth is being utilized at the time by which MNO. Thus, a probable simultaneous utilisation of the spectrum, results in poor SINR and erroneous CQI estimation for the users. The authors propose that the MNOs in adjacent area to be connected through an interface such as the backhaul, or a central management entity, so that they inform each other which part of shared bandwidth is being utilised by each MNO at the time.

This problem, however, can be relaxed, assuming the bandwidth is shared only upon demand, and only the MNO that demands for shared spectrum transmits reference signal over the shared bandwidth, and therefore, its associated users can detect the signal without the concern of interference. Moreover, the signalling overhead due to the real-time coordination can be significantly reduced.

Spectrum Sensing Based

In [34], the sensing technique (energy detection type) is applied upon demand to distinguish whether the bandwidth is occupied or free, with no direct interaction between the MNOs. Only specific users involved to perform sensing, and report the results to their associated BSs, in a specific area (not the entire cellular network is deployed), and signalling overhead is assumed to be negligible. However, given the fact that the spectrum allocation in the LTE-A varies in each subframe, sensing results will be invalid when sharing is performed in a time granularity of subframe level. Besides, miss-detection (a known problem in the sensing techniques), when there is no interaction between the adjacent BSs, results in poor detection of interfering signal in large-scale cellular networks with frequency re-use one. Thus, applying sensing technique solely without any interaction/coordination between the adjacent cells is not reliable enough. The deployment of Wireless Sensor Networks (WSNs) is investigated in [110], in order to capture SOPs in a more reliable manner compared to the case that sensing is performed by the UEs such as in [34] (due to limited capability of UEs to recognise that a particular channel is being used within other nearby cells). It is stated that, this approach can provide detailed information of spectrum usage status/SOPs on a real-time basis. The sensors are connected and cooperate via wired or wireless links to exchange information (i.e., SOP status) across the entire network. They can be shared between the several MNOs so that the BSs belonging to each MNO in a specific area can communicate with the corresponding sensor node, and reduce the cost of deployment. Although this approach shows improvements in terms of reduced packet drop rate compared to the case of non-sharing, the impact of additional costs for MNOs and the signalling overhead for communication among sensor nodes is stated to be an issue.

4. Spectrum Pooling

Beamforming Based

The authors in [135], and [111], apply coordinated beamforming technique in IOSS. As explained earlier, this technique facilitates flexibly modifying the phase and amplitude of the signals from each radiating element inside the antenna to shape and steer the direction of the radiated beam vertically and horizontally. Thus, the MNOs in adjacent area simultaneously can serve UEs over the same bandwidth (this type of sharing is also referred to as non-orthogonal sharing). However, applying this technique is subject to sharing of CSI between the MNOs to avoid destructive interference. Besides, it should be noted that the MNOs must own dedicated bandwidth for the transmission of their control channel, which cannot be transmitted over the shared spectrum.

Meta scheduler/CQI based

In [83], a common pool of shared spectrum is considered, for the case of two MNOs deployment, and sharing procedure is managed by a centralised scheduler (also referred to as meta/super scheduler) to assure exclusive access to the shared spectrum to avoid inter-operator interference. The scheduler is assumed to have a connection with the respective BSs and allocates the shared bands in a mutually exclusive way to the UEs with the best CQI in order to achieve the maximum cell capacity. Thus, no fairness/priority of access criteria are to account.

The performance of this approach as a function of traffic load correlation are discussed for varying percentages of sharing ranging from 0% to 100%. The total sum capacity, which is defined as the sum of achievable Shannon capacities on each allocated sub-channel, shows improvement compared to the non-sharing case. The upper bound limit of up to 20% is shown. However, similarly to the other centralised approaches, in this work the negotiation among the MNOs and the meta scheduler requires additional resource. Besides, the scalability of this approach in the case of multi-cell/multi-MNO deployments has not been evaluated. Therefore, it is not clarified how a meta-scheduler contributes in SS to manage multiple cells.

The SOTA approaches of the IOSS are highlighted in Table 2.2.

Table 2.2: Summary of SOTA approaches of IOSS

Deployment scenario	**Spec./incorporated coordination tech.**	**Advantages (+) and Shortcomings (-)**
Inter-operator/ National Roaming	=> UE senses reference signal of host BS => No additional infrastructure is required	+ 10% improvement in EU or cell throughput compared to the case of non-sharing - Low gains in cases of symmetric traffic - Increased delay, due to handover messaging procedure
	=> RNC is shared between MNOs (in both collocated and non-collocated RANs)	+ Roughly 32% increase in cell capacity - Low gains in the cases of symmetric traffic
Multi-operator Virtual RAN, and Spectrum Sharing	=> RAN is shared between multiple MNOs	+ Enables significant reduction in CAPEX in low traffic areas + Facilitates spectrum sharing procedure among the MNOs - Requires virtualisation capable infrastructure
Mutual Renting	=> Sensing capable UEs detect the available spectrum => The sensing information is sent to the respective BS	+ Except sensing capable UEs, no additional infrastructure is required + Real-time spectrum opportunity detection - Vulnerable to cognitive sensing related issues such as false alarm and detection, hidden node problem. - Short time scale sharing results in interference, unless MNOs synchronised
	=> Spectrum availability is broadcasted by small cell BSs => No additional infrastructure is required	+ Roughly 7% improvement in terms of average user throughput - When MNOs have symmetric traffic load, gain will be very low/zero - Gains are subject to MNOs agreeing to broadcast their operator specific information
	=> Spectrum opportunities are detected by distributed wireless sensors	+ Is shown to be effective in reducing packet drop rate + The cost of deployment can be shared among MNOs - Requires backhaul to connect sensors and BSs - Vulnerable to sensing related issues in indoor and mountainous areas
Spectrum Pooling	=> Centralised super scheduler allocates shared bands => Decision is made based on the CQI of the UEs regardless of their home operator	+ 20% increased cell sum capacity (upper bound) - Fairness is not guaranteed among UEs of different MNOs - Requires real-time interaction between BSs and super scheduler
	=> Coordinated beamforming	+ Increased spectrum utilisation efficiency - Requires sharing of CSI between MNOs - Requires interconnection among BSs of MNOs - More beneficial for the users with high SINR, close to their serving BSs
	=> Game-theory based approach => Cooperative games perform based on pre-sharing agreements among MNOs	+ No need for real-time inter-MNO information sharing - Efficient and fair policies are complex to implement

2.5.2 Licensed Shared Access (LSA)

In addition to the IOSS, the LSA framework also is investigated through various approaches so far. Initially, experimental live field trials carried out, in compliance with the standard reference LSA architecture [136], resulted in a time/location limited SOPs, subject to immediate evacuation of the shared spectrum by the cellular network, when an incumbent user reclaims the spectrum (which is informed through assumed low latency and reliable interfaces) [137].

In a most recent work, the interference imposed by the cellular network is approximated through the statistical propagation models, considering a predefined interference threshold to identify the potential interfering radius. Upon arrival of the incumbent, the advanced features of mobile cellular network (namely LTE-A) such as; power adaptation, beam-steering with antenna tilting, and Self-Organizing Network (SON) are applied [37], [117], [119], and [138]–[141]. The intention mainly is the cellular network to react efficiently in a sense that, without the need to always evacuate the entire shared bandwidth, service disruption probability of the LTE-A users is reduced, while the interference to the incumbent users is still avoided.

The downside of the propagation-based approaches is twofold. Firstly, unlike mobile cellular networks, not much information (i.e., actual radioelectric parameters, such as antenna height, terrain based or over the air, etc.) from the incumbent user is known, and therefore, no proper propagation pattern is modelled so far. The lack of accurate propagation model between the incumbent and cellular networks' transmitters, has resulted in applying conservative propagation models to estimate a worst-case scenario of interfering signal [37], [138]. As a consequence, it does not identify the exact overlap area of incumbent with cellular networks. Thus, even though the presence of the incumbent is informed through an interface, a wide coverage area of cellular network is identified as an interference zone (even though the incumbent overlaps only with part of the cell(s)). This method is even more challenging in the LTE-uplink transmission mode, as the position of UEs changes over time due to mobility and environmental

Table 2.3: Summary of SOTA approaches on LSA framework

Project/Paper	**Incorporated technique**	**Aim**	**Impacts**
LSA trial demonstration	SON is integrated in LSA controller and incumbent user movement tracking	Reduction of delay in LSA band-evacuation phase, and a more robust incumbent interference protection.	Delay reduced to 85%, from 21s (former trials) to 3s, and a 18% capacity improvement
"Optimisation of Authorised/Licensed Shared access"	Power adaptation and beam-steering in LTE network	To protect incumbent users from interference while incorporating 2300 MHz bands for LTE use.	30% improvement in average. user throughput outside of the exclusion zone (where incumbent users do not exist), and 10% improvement in average user throughput within the exclusion zones, with power reduction and downtilt.
"RED Technologies", "ADEL"	Radio Environment mapping	More dynamic and accurate spectrum opportunity detection.	Project ongoing.

factors so the interference probability varies over time.

In [142], and [143], the authors mainly focus on allocation of the LSA bands when multiple MNO co-exist (rather than focusing on detection of SOPs) and propose fairness-based solution. However, these approaches are not the main target and do not pertain to performance improvement of LSA framework itself to identify LSA related SOPs. A summary of SOTA LSA approaches is presented in Table 2.3.

2.6 Summary and Discussion

In this Chapter we comprehensively studied licensed spectrum sharing schemes for mobile cellular systems, various existing sharing scenarios/approaches with different network topologies, and also investigated their features, challenges and probable use cases.

From SOTA of IOSS, we learnt that the inter-operator roaming scenarios are the most straightforward types of sharing in terms of deployment. Subject to pre-agreement among the MNOs, inter-operator roaming can be simply performed between two corresponding cells. However, this sharing method is dependent on the load of the host MNO. In the case of mutual renting and spectrum pooling approaches, it is observed that, lack of efficient coordination schemes results these schemes to be applicable for the limited number of deployment scenarios such as; 1) indoor small cell deployments with low power BSs and geographically separated/isolated coverage area with lower risk of interference, 2) where UE is located close to its serving BS with reasonable signal strength in outdoor scenarios, 3) where capacity demand asymmetrically varies among the sharing players (the MNOs here), so that they have some spare spectrum to share. This problem limits the gain can be achieved through SS, and results in a lack of interest to proceed for the real-world deployment.

Moreover based on the SOTA of LSA, we learned that applying LSA in mobile cellular systems obviously provides an additional spectrum, and improves system capacity. However, due to the sensitivity of incumbent systems in terms of interference, LSA-based sharing approaches must ensure that mobile cellular systems do not impose harmful interference. Moreover, depending on the nature of the incumbent systems, the availability of LSA bands may dynamically vary over time/location (i.e., the amount of bands may increase, shrink or even reclaimed by the incumbent). Therefore, the LSA bands should be considered as a complementary way to achieve additional capacity. Therefore, any implementation of LSA requires extensive experimental performance evaluations in advance in order to determine the achieved gain, while considering the costs of deployment (e.g., additional required components/infrastructure, hardware, software modifications, etc).

From the spectrum perspective, 5G networks will need to be able to operate over wide range of frequencies from sub-1GHz up to and including mmWave frequencies (spanning 10-to-90GHz). Lower frequencies will make up a key part of the spectrum used in 5G, for services requiring very low latency, ultra-high reliability, higher data rates and wider bandwidth. The low-frequency range will be complemented by high-frequency deployments that will be able to deliver very high data rates and capacity in dense small-cell deployments. The sharing schemes such as, LSA and IOSS will enable 5G networks to have greater flexibility for the capacity provisioning, if the coordination between sharing players is performed to avoid interference. On the other hand, from the spectrum regulators' point of view, spectrum sharing can improve spectrum utilisation when/where bands are not utilised by the actual license holders. However, due to the user diversity and traffic correlation among operators, it is not always possible to achieve constant capacity gains.

It can be concluded that although the progress seems promising, a lack of efficient and cost-effective sharing schemes can still be observed. Although, the shared use of spectrum introduces some complex issues such as interference to the systems that are currently operating in exclusive bands, but they do not seriously impede the deployment of spectrum sharing if they can be mitigated/avoided by enhanced interference management approaches. An efficient sharing scheme can be implemented with further enhancements in joint PHY, MAC, network, and even application layer protocols to perform robust interference management, and accurate and fast sensing with least possible signalling overhead to get the most benefit of a sharing scheme.

2.7 Further Research Directions

The enhancements and developments of the following coordination techniques as potential solutions (which are likely to be part of the next evolutionary steps of the future of IOSS and LSA) are recommended in this section.

1. **Inter-Operator ICIC/Coordinated Multi-Point (CoMP)**

   The ICIC/CoMP technique (which is supported by 3GPP LTE-A specification), is applied in a way that multiple BSs of different sites cooperate to improve the cell edge user data rate and spectral efficiency. The key role of CoMP in *intra*-operator scenarios is to avoid/mitigate interference to the UEs served by neighbouring BSs scheduled on the same frequency (when frequency re-use factor is one, i.e., the same frequency bands are assigned to all cells belonging to the same MNO). This technique is similar to the technique(s) which are required to address the problem of inter-operator co-channel interference, due to the shared usage of spectrum.

There are two major types of CoMP; the first one refers to as joint scheduling which is performed by the adjacent cells to the specific UE (typically at the cell edge). In this case, only CSI of the UE is exchanged between BSs to choose the BS for the transmission. However, in the second type which is known as joint transmission/processing, both CSI and UE data is exchanged between BSs due to the reason that both BS transmit to the user at the same time [144]. Thus, it is reasonable to expect that the BSs which support CoMP technologies could be able to support inter-operator spectrum sharing as well, as it has the same requirements on synchronisation as in CoMP [78]. However, CoMP is now only applicable for intra-operator scenarios, and also requires the exchange of CSI and also user data with specific reference signals to perform joint precoding over a fast backbone connection (e.g., X2). Thus, the deployment of inter-operator CoMP technique, to manage the co-existence of the MNOs on the shared bands, requires that all the adjacent BSs (of the different MNOs) to be connected through, e.g., X2 interface to each other as well as sharing of some control and user data between them [78].

2. Enhanced Inter-Operator Coordinated Beamforming

The deployment of beamforming as a potential coordination technique, when MNOs simultaneously (pooling basis) operate on shared spectrum in the same area, studied in detail. However, there are important open issues that should be solved for the real deployment of this technique in inter-operator spectrum sharing. As mentioned earlier, the CSI needs to be shared among the corresponding BSs of different MNOs as well as interfering CSI among BSs of one operator and UEs of the other operator. Such information exchange needs to be carried out in a reasonable time scale (i.e., smaller time scale than the channel coherence time, which refers to the duration on that the band is available [145], and [146], through an interface with reasonable capacity/speed. Similar to the case of inter-operator ICIC, the point-to-point coordination and information exchange are subject to additional cost as well as the satisfaction of participating MNOs. Enhanced coordinated beamforming techniques with minimum to no sharing of information between MNOs, are highly preferable.

3. Enhanced Spectrum Sensing

A wide range of sensing techniques have been proposed and investigated in CRNs. We briefly discussed the shortcoming of this technique such as lack of certainty, earlier in this Chapter. However, in the context of licensed spectrum sharing, sensing techniques will play an important role as complementary trends in conjunction with other techniques (e.g., the Geolocation database). Thus, enhanced sensing techniques will be required that can capture spectrum availabilities across the network in a more reliable manner and reasonable time scale with respect to resource allocation granularity in mobile cellular networks, and on the other hand shared spectrum availabilities. Some factors such as reduced energy consumption for UEs (or any sensing capable device) while performing sensing, reduced sensing time duration, will be the representative targets of spectrum sharing schemes.

4. REM Technique

The deployment of REM is expected to be noticeably beneficial as a hybrid (combination of sensing and database) coordination technique in SS, and has been addressed in sharing schemes such as TVWSs sharing [147]. Given the discussion presented in Section 2.5, this technique can potentially contribute to mitigate the challenges of deployment of IOSS and LSA. More precisely, in the context of IOSS, REM helps to detect SOPs in a more concise (i.e., considering SD-TD SOP awareness) manner and consequently reduces the risk of interference and provides more room for SS (with respect to the conservative approaches, namely [33]).

Moreover, the LSA is expected to be one of the key tools for capacity augmentation in 5G networks. However, the existing functionality of LSA framework is static in nature (with rather a wide temporal/geographical exclusion zones to ensure strict incumbent interference protection). As discussed earlier, the predetermined wide exclusion zones have resulted in the LSA spectrum to be more suitable for the low power small cells (typically indoor) with sufficient geographical separation. However, in 5G networks, small cells may utilise higher frequency ranges (e.g., mmWave), and LSA bands are expected to be in demand for outdoor uses. In conclusion, the evolution of LSA framework requires the adoption of techniques which can lead to a more dynamic spectrum allocation between the MNOs, as well as dynamic LSA-SOP detection.

From the SOTA of REM (in Chapter3), practical deployment of REM itself faces several general/pre-known challenges, and in this respect, many questions yet to be answered, which necessitates broader research in this field. More precisely, to update the database in a dynamic manner excess signalling load will be imposed on the network, and therefore ideal backhauling, between the REM components will be required. Thus, the level of dynamicity of the network will affect the algorithmic complexity of the deployment, more specifically when the time scale of sharing is short (e.g., in the order of ms). Besides, the optimal area of coverage by REM must be investigated. It should be determined whether to develop local (e.g., multiple REM, city-wide) or global (e.g., countrywide) REM. In the case of local REM, multiple deployments per MNO will be required which imposes costs and also synchronisation between REMs resulting in more system complexity.

On the other hand, wide area coverage (i.e., country wide) reduces accuracy of information and degrades the performance of REM (due to the considerable time duration for keeping the database up-to-date). Other challenges, such as unknown optimal number of sensor nodes for the purpose of measurements (i.e., the trade-off between the accuracy of measurements and number of nodes), lack of accurate geolocation measurement for indoor cells, energy consumption of UEs (in the case that UEs participate in measurements), all will require comprehensive investigations [148].

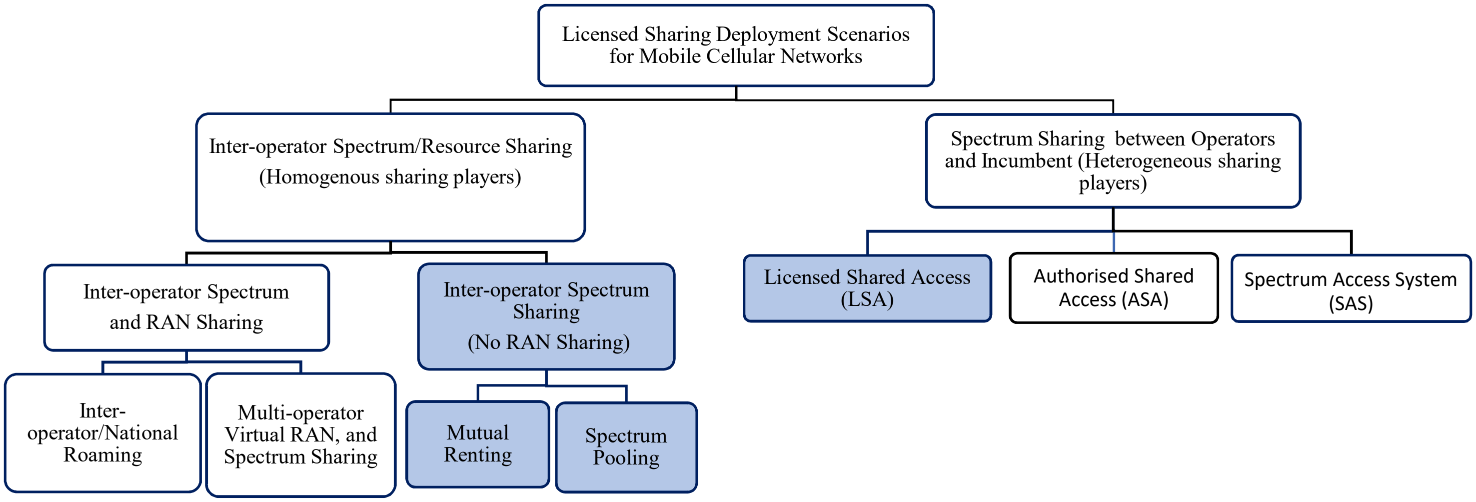


Figure 2.9: Taxonomy of Deployment Scenarios. The shaded blocks represent the scope of this thesis.

Despite all the challenges of REM, Europe now pilots LSA, applying REM techniques, in order to evaluate and plan the practical LSA deployment, localise zones for spectrum sharing geographically and minimise the probable interference between the incumbent and the LSA licensees [149], which indicates the important role of this technique for the mobile cellular networks. The outcome of this investigation was not published.

Based on this discussion, the rest of this thesis the focus is on investigation and analysis of REM technique in both IOSS, and LSA framework. First the feasibility of this technique is investigated and further on, some of the challenges are addressed for improvements. The scope is highlighted in Figure 2.9.

Chapter 3

REM-Enabled Inter-Operator Spectrum Sharing

3.1 Introduction

In this Chapter, first, a study of SOTA REM is conducted. The methodologies are identified, as well as the use cases and the common challenging issues of the deployment. Moreover, a set of important assumptions that have been made to facilitate implementation of REM are pointed out. The end goal of this study is to get a broad overview of all possibilities of the REM deployment to identify the most reasonable method (considering the characteristics of the mobile cellular networks) for the SS purpose.

Further on, a novel REM-based IOSS mechanism between two independently deployed MNOs in the downlink[1] of LTE-A, is proposed. It is shown that the proposed IOSS mechanism can provide far better performance compared with the conventional approaches in [33], and [34].

[1]Representing the scenarios in which only the BSs are interferers and UEs are victims of the interference.

3.2 REM Methodology

3.2.1 Concepts

Radio Environment Map (REM)[1] involves a set of network entities and associated protocols that trigger, perform, store and process geolocated radio measurements such as; RSS, to identify interference levels. Such measurements are typically performed by the UEs, or network entities such as dedicated sensors. The REM uses a database capable of tracking dynamic changes in the network [148]. The database stores multi-domain environmental information and prior knowledge, such as the geographical features, available networks and services, spectral regulations, locations and activities of radios, policies of the users and/or service providers, and past experience.

More precisely, REM is description of power over particular frequency bands/bandwidth at each location and time of interest. The sensing/measurement of RSS at certain locations are performed (and as it is not possible to perform sensing at every single location in wide networks) in conjunction with the statistical interpolation or propagation models, and predefined (tolerable) interference thresholds, the interference fields are mapped/modelled and SOPs are identified across the network. That is what the term REM mean; Map of the radio environment (or interference map).

It can be considered as a powerful technique that encompasses any compliant reconfigurable RAT, which provides synthesised view of the networks for monitoring purposes [150]. REM can be implemented by independent and unbiased party such as spectrum regulators. Based on use cases and varying environment (location of users, signal strength, propagation losses) it must be constructed either periodically or upon a request, on a timely manner to capture the network dynamics.

A generic description of the REM concept (irrespective of in which RAT is applied) is provided in Figure 3.1.

[1] The terms spectrum cartography, interference cartography, are also used in the context of REM.

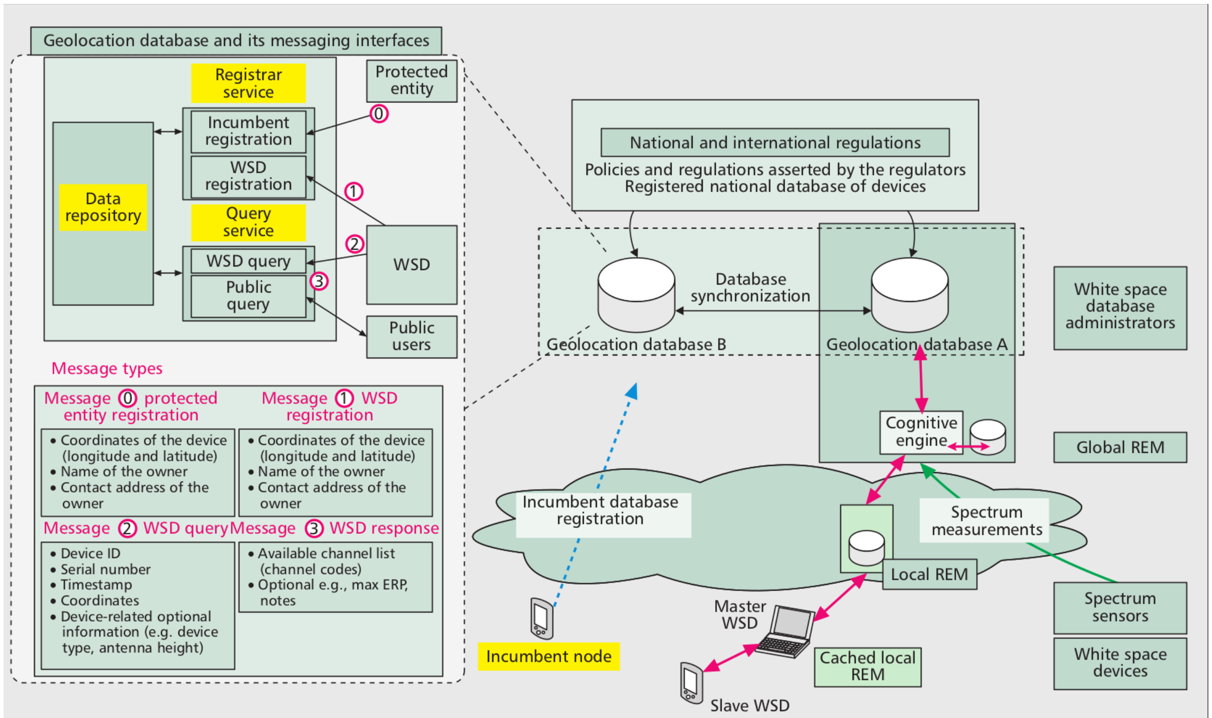


Figure 3.1: REM concept. (Figure is from [148])

As shown in the Figure 3.1, geo-located measurements are collected by the sensing capable devices from any RAT domain and are stored and treated in the REM entity. The post-treated REM data is then provided to the RRM entities for radio resources optimization purposes [148].

3.2.2 Use Cases

The REM concept is not new. It has been broadly investigated in various spectrum related problems in the SOTA, for instance, in the mobile cellular networks for the identification of coverage holes [151](for the Minimisation of Drive Tests (MDT)), as well as for derivation and estimation of interference to synthesize a reliable Radio Interference Field (RIF) (also known as interference maps) for the purpose of RRM optimisation [150] in intra-MNO scenarios. Moreover, it has been applied as an enhancement of geo-location database for sharing of the TVWS [152], [153].

3.2.3 Enabling Techniques and Assumptions

As of SOTA, the spectrum maps can be characterised and modelled in two different ways. In both methods the location of sensors (or any device performs sensing) must be known. The fact that which method should be chosen depends on the application, how data will be modelled, and is subject to availability of the information from the involved systems:

1. **Sensing-Assisted Propagation based REM**

   The RSS measurements through sensors assist database helping offline propagation models to locate the source of transmitters and potential area of interference for the receivers. This method assumes that transmitters configuration such as; transmitters power, antenna pattern, its azimuth, and information of propagation environment (homogeneous terrain (flat) vs heterogeneous terrain (hilly)) are known. Th performance is highly dependant on propagation models, and thus, there is a need for extremely accurate and realistic propagation model so that the location of the transmitted can be precisely predicted. These statistical models are not always efficient specifically for real-time high precision prediction of signal propagation.

2. **Sensing-Assisted Interpolation based REM**

   Field measurement values are sampled on a regular grid/or random placement of sensors. In the locations where the measurements are not available, the power is estimated through interpolation techniques, and the aggregate interference in the entire network is modelled in this way. Under his method almost nothing is known of transmitters; such as source of power or exact locations transmitters. Varieties of interpolation methods are available, which are applied based on the research problems in various scientific areas. Each method falls in one the following categories [147], [154], [155]:

   Local neighbourhood approaches: In the interpolation methods under this category it is assumed that the impact of a spatial measured point is limited with the distance. The interpolated values are computed by predefined functions that reflect the neighbouring points influence. The most commonly used methods in the literature are Inverse Distance Weighting (IDW), Natural Neighbour(NN) and Triangular Irregular Network(TIN) interpolation.

Geostatistical approaches: The interpolation under this technique rely on statistical models that are based on the "theory of random functions and variables to model the uncertainty associated with the spatial estimation process". The most widely used geostatical interpolation is based on the kriging method and its variations. These are essentially optimal linear interpolation techniques in the sense of having minimum Root-Mean-Squared-Error (RMSE).

Variational interpolation approaches: The interpolation methods under this category are based on the assumption that the interpolation function should have very small deviations from the measured points while tending to be as smooth as possible. These two requirements are combined into a single condition that represents a spline function reflecting the interpolation method. The Thin Plate Spline (TPS) interpolation is the most widely used variational interpolation methods.

The most widely used interpolation methods in REM are explained below:

- **Nearest Neighbour:** Bsed on this method the interpolated signal value P_{rx} at location (x, y) always adopts the value of the closest signal measurement P_i at location (x_i, y_i), $i = 1, ..., N$ (select the measurement with the minimum Euclidean distance) [156]. This method is known as most efficient computationally, but the least accurate as it does not conciser the influence of the sample data points in further distances.
- **IDW:** The IDW interpolation is also referred to as a Shepard's method [154]. It is assumed that spatial measurement samples which are close to each other, are more similar than those which are in further distance. Assuming

the measured signal values are P_i, $i = 1, ..., N$ at locations (x_i, y_i) in the surrounding of the interested location (x, y), to the interpolate signal value P_{rx}. Each measurement P_i is weighted with the weight w_i calculated as the inverse of the distance d_i between the locations (x, y) and (x_i, y_i) The rate of weight is decreased as a function of distance.

- **Kriging:** This method is a weighted average interpolation technique meaning that; to estimate the signal level P_{rx} (x, y) at location (x, y), the distances and the degree of influence between the signal measurements are considered. To obtain the corresponding weights, unlike IDW, in Kriging method instead of the inverse of the respective distances, the spatial correlation between the sample data points is employed. The weights are chosen such that the variance of the kriging estimator is minimized. A degree of relationship (i.e, the weights) between the signal levels on all locations is estimated using a "semi-variogram/variogram analysis" (the theoretical semivariogram model can be chosed), which is defined as a measure of the statistical dependence between two points based on their values and the distance between them. [154], [10], [157][1].

  Although Kriging requires more measurement points, it is the most commonly applied technique in the literature due to its higher precision [10], [158]. It is a linear unbiased estimator that yields a zero mean residual error[2] and minimizes the error variance. Other Kriging interpolations differ in the assumptions made about the mean of the random field, e.g., Ordinary Kriging assumes that the mean is constant in value but unknown [154]. In Fixed-rank Kriging [151] it is stated that the computational complexity of Kriging is reduced with linear computational complexity for large scale networks and massive data. [159].

  Both Kriging and IDW, because of highly parametric formulation can be

[1]All detailed mathematical explanation can be found in [157].
[2]The vertical distance between a data point and the graph of a regression equation.

computationally complex in time and cause delay to produce the results. Lowering the number of parameters used or choosing simpler fitting technique will decrease the processing time but sacrifice the accuracy[154]. The complexity also can be reduced by simplifying assumptions such as limiting the area of observation where exactly the estimation is required rather than the entire network. Based on [154], and [10], compared to IDW, the Kriging produces superior performance with lowest interpolation error, in estimation of interference area.

3.2.4 Known REM Deployment Issues

As any technique, the implementation of REM encompasses challenging issues, which depending on the exploited methodologies can vary.

Depending on the size of the network, and the dynamic of the network (granularity/resolution of REM information) monitoring the instantaneous aggregate interference in real-time with unpredictable nature of signal propagation is challenging, specifically when the users across the network have unpredictable activity (received power from the UEs varies depending on the UE position within a cell as well as other environmental factors)[10]. If the UEs are pedestrian/still, then previously constructed REM will be more similar to the REM of a few seconds later, compared to the case where the UE is in a car. Deciding on the REM update intervals is one of the challenges considering the mobility of UEs that makes the interference changing over time (in the case of Uplink of Cellular networks where UE is the source of interference). The delay due to REM information dissemination delay, leads to REM information inaccuracy.

The accuracy of REM, can be improved by increasing the number of sensors/densities, their distribution in the network and sensing capabilities. Number of sensors per particular area helps to reduce hidden node problem and also capture noise uncertainty better. However, apart from the cost of deployment, computational-time complexity of processing of massive data is a challenge. Therefore, there is a trade-off between overhead and accuracy. It can be expected by knowing current situation and leveraging the prior knowledge via prediction algorithms, the computational-time complexity of processing of dynamically varying data, and adaptation time can be reduced and faster adaptation can be achieved.

Moreover, some of the interpolation techniques suffer from sparse measurements and fail to capture SOPs in larger scale networks with massive measurement data. The impact of channel and noise impairment, correlated shadowing, noise floor uncertainty dependant issues from the context of cooperative sensing. However, these challenges can be mitigated by exploiting appropriate interpolation method and/or accurate propagation models.

In the context of SS (within the scope of this thesis; i.e., the IOSS and LSA), the REM has not been applied for inter-MNO sharing scenarios so far. However, in the context of the LSA few works have investigated the application of REM. For instance in [10], and [143], the authors have focused on cooperative sensing issues of REM. In [153], although REM has been considered, the main focus in on allocation of LSA bands between multiple MNOs, and no further information regarding how REM has been implemented is provided. Thus, these works do not pertain to performance improvement of LSA scheme via REM. Besides, the investigation of impact of REM in the co-existence of MNOs and LSA incumbent has not been addressed in the SOTA, which is addressed in this thesis.

From the category of REM construction technique, the second one, i.e., the sensing assisted interpolation-based REM is applied for the scope of this thesis, where the location of e.g., the UEs (transmitters and receivers in general) is not known. Given the discussion above choosing interpolation technique is application specific (indoor/outdoor, cellular networks, WLAN, TVWSS, etc.), and each technique has its pros. and cons such as; high/low level of required measurements, high/low accuracy, computational complexity of data, performance of some of them is affected by the large scale fading, some of them are not suitable for large scale networks, some of the are not accurate enough for a specific applications. So where accuracy matters such as SS scenarios, there is a need to choose methods with least possible error. Out of available interpolation techniques, Kriging is applied. As dicussed earlier in this Chapter, although it is computationally complex and needs high volume of measurments, but it is the most accurate one. As of [151], and [159], it is found as the most computationally feasible method over large-scale mobile cellular networks with massive measurement data is Fixed Ranked Kriging which will be investigated in our future works.

3.3 REM-Enabled Inter-Operator Spectrum Sharing

The deployment of IOSS is of great importance for mobile communication networks. It enables to exploit variable-size underutilised spectrum to meet their continuously growing capacity as well as wide bandwidth demands, with lower fees [160]. Overall, it results in efficient utilisation of scarce spectrum. However, as interference is introduced as a main limiting factor of the deployment, conservative sharing policies/protocols and/or strict assumptions are applied, resulting in limited gain by IOSS.

In this respect, in [33], multi-cell layout (more realistic network deployment scenario) is considered for IOSS between two independently deployed MNOs. A centralised third-party entity assumed as a message exchange interface to manage the coordination (regarding the bandwidth is being shared upon demand) between the MNOs, to avoid risk of interference. In the multi-cell network layout with frequency re-use one, all the cells/sectors belonging to the supply MNO surrounding (i.e., overlap partially or entirely) the cell/sector of the demand MNO, must cease operating on the shared spectrum to avoid interference. This means that multiple cells/sectors of the supply MNO must share spectrum with one demand cell/sector. As it is unlikely to find the same set of free RBs in all the cells at the same time, limited-to-no spectrum sharing gain is shown. One solution can be to monitor load/SUT of the adjacent cells for a specific period of time and free the same set of RBs from all the cells for the purpose of sharing. However, this solution will be very much dependant on the load in each cell and might not be a generic solution.

The IOSS between the two MNOs, is investigated in [34], where sensing technique (energy detection type) is applied upon demand to distinguish whether the bandwidth is occupied or free, with no direct coordination between the MNOs. Only one cell per MNO is considered, and also specific users are involved to perform conventional hypothesis test[1] between H_0, and H_1, and report the results to their associated BSs. However, given that there is no coordination between the adjacent BSs, and the geolocation information of the UEs that perform sensing is not considered/known, this policy may result in wrong decision by the BS, regarding the status of a particular RB (occupied and idle) in large-scale cellular networks (i.e., multi-cell deployments) with frequency re-use one (an RB might be identified as occupied at one part of a cell, and as idle at other side of the cell). Thus, applying sensing technique individually without any coordination between the adjacent cells is not reliable enough.

The SOTA of IOSS approaches perform based on either simple (just as a coordinator) centralised coordination, or sensing technique. Due to the lack of inter-operator ICIC coordination, and lack of awareness of spectrum utilisation in all surrounding cells for detection of interference-free SOPs, low/no IOSS gain over large-scale networks is achieved. None of these works characterises combination of sensing and centralised decision making technique, which models the spatial-temporal SOP awareness. Hence, in this Chapter, spectrum cartography in the context of REM is applied to identify SOPs in IOSS in mobile cellular networks, to address this problem.

[1] When a cognitive device performs sensing (Energy Detection, ED [161]), Energy (E) values can be sent to a central entity termed as fusion centre to perform a hypothesis test for a final hard (0 or 1 binary decision.) Alternatively the sensors can make the hard decisions and just sent it to the fusion center. Depending on the requirement for the accuracy these methods can be employed. In general depending on the kind of signal being transmitted by an active transmitter, the optimal detection strategy would differ. For instance, the signal could be either wideband/narrowband, frequency-swept signal, frequency-hopping signal, etc. For each of these, the REM is required to employ a different detection strategy such as ED, matched filter, cyclostationary feature detection, etc. For the scope of this thesis, these signal dependent detection strategies are not detailed.

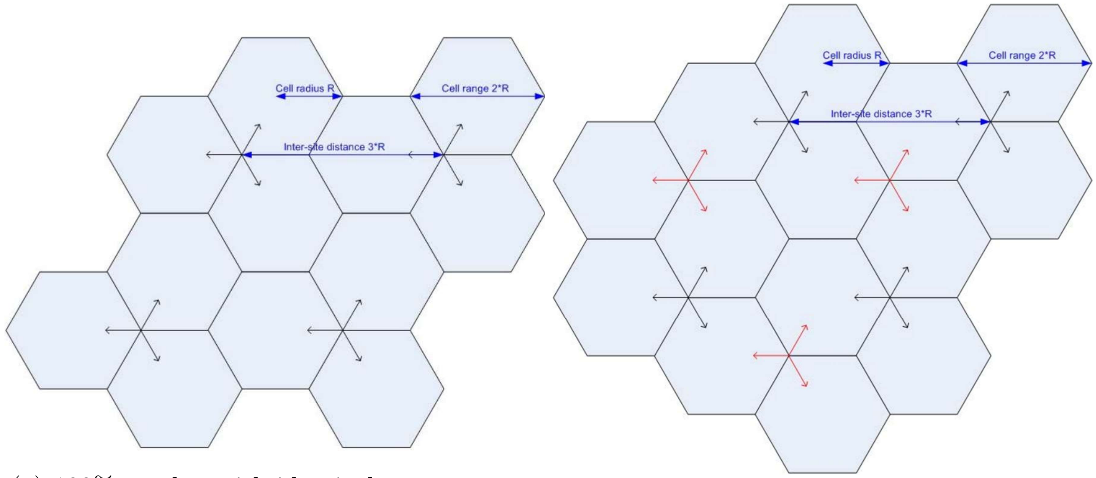
3.3.1 System Model

The system model includes two MNOs underlying homogeneous (i.e., one-tier network including only macro cell BSs) conventional cellular topology in LTE-A (the LTE-A specifications are learned from [162]) in the downlink. The topology of two MNOs relative to each other is considered with; (a) 100% overlap (collocated), and (b) partial overlap (non-collocated), where identical cell layouts for the MNOs, but with worst case shift between sites[1], is considered (where the demand MNOs' sites are located at the supply MNOs' cell edge. These topologies are justified by [33], and 3GPP [36], and are envisioned to effectvely investigate all the possible aspects of deployment co-existance.

From a practical point of view, 100% overlap deployment is justified in the cases that, multi-MNO RANs, due to deployment limitations such as absence of sites [36] is preferred. The illustration of the two possible multi-MNO topologies are depicted in Figure 3.2. The BSs are assumed to support multi-carrier functionalities such as the CA technique [36]. Thus, they may utilise the shared bands in aggregate with the owned bands, or just perform traffic steering at connection setup to serve their UEs with the additional bandwidth. Besides, it is worth pointing out that, it is necessary to assume part of the bandwidth is dedicated for control channels and cannot be shared (or alternatively data and control separation architecture can be assumed which is out of scope of this thesis).

Based on the statics provided in [163] from the real environments, the traffic across each MNOs' network is considered unevenly (each cell has different number of UEs to represent spatial variability of load/traffic) distributed, which represents the overload and underload cells. This assumption is reflective of spatial and temporal traffic dynamics in the underlying systems. Thus, the scenarios in which there is a need for spectrum sharing, and in parallel the SOPs are available for sharing can be modelled in this way. Without loss of generality, to simplify implementation and analysis, here one

[1]Apart from the geographical offset between the BSs, these two topologies can be distinguished by different antenna orientation in the cells (Figure. 4.1(b)).



(a) 100% overlap with identical cell layouts for both MNOs

(b) Partial overlap.The sites of the demand MNO are shown in red.

Figure 3.2: Underlying multi-MNO system models for IOSS scheme [36]

directional sharing, i.e., one MNO as a supply and the other one as a demand MNO is considered (the same as [33]). Moreover, from [33], it is already learned that the upper bound capacity gain of IOSS is limited by the traffic correlation of two MNOs. Thus, it is assumed the traffic between the two MNOs in an area of interest is uncorrelated (the peak hours may coincide, but the UEs traffic, such as voice call, etc. in the cell belonging to two MNOs in a given area is not exactly the sam [164]) to be able to identify SOPs.

A metric termed SUT as of in [33] is considered which is defined as a percentage of RB utilisation in each cell per TTI, and $\overline{SUT}$ when averaged over specific time (The past 100 Transmission Time Intervals (TTIs) in this work[1]), and is calculated and monitored by each cell to alarm for overload status as follows:

$$SUT_{j,s}^{BW_{Own}} = \sum_{r=1}^{R} \alpha_{j,s,r} \quad \text{where} \quad \alpha_{j,s,r} = 1 \quad if \quad RB_r \quad \text{is utilised, and 0 otherwise.} \tag{3.1}$$

Assuming BW_{Own} has R number of RBs, $SU_{j,s}^{BW_{Own}}$ represents spectrum utilisation

[1]This can be amended to any optimal value.

per TTI_j and per $cell_s$, and is averaged over past 100 TTIs as follows:

$$\overline{SUT}_{t,s}^{BW_{own}} = \frac{1}{100} \sum_{j=t-100}^{t} SUT_{j,s}^{BW_{own}} \qquad \text{where} \qquad t \geq 100 \tag{3.2}$$

This metric is compared to a predefined threshold[1] by the MNO to declare whether a cell(s) is overloaded.

As discussed earlier, interference is the major concerning issue in SS that has to be modelled and mitigated/avoided efficiently. Here we explain how single MNO interference modelling with no SS is different than two-MNOs deployment when SS is applied.

Assuming multi-cell single MNO in LTE-A scenario with frequency reuse 1, the (co-channel) intra cell interference in the SINR metric is emplyed to identify the real value of the recived signal strength at UE side to identify its status for resource allocation (at the beginning of each TTI where the RBs have not been allocated to the UEs yet). As of baseline LTE-A, the downlink wide-band SINR[2] experienced by UE_u at each TTI_t is modelled as follows [165]:

$$SINR_{u,t}^{BW_{own}} = \frac{RSS_{serv.}^{BW_{own}}}{\overline{\eta} + \sum_{s=1, s\neq serv.}^{N} RSS_{s}^{BW_{own}}} \tag{3.3}$$

Where $RSS_{serv.}^{BW_{own}}$[3] represents the received signal strength from the serving BS. The

[1] There is no confirmed/standard value for this threshold, and must be agreed between the MNOs, under NRAs. As of [33] it can be specified by the MNOs. For instance the supply MNO can be conservative, and define this threshold very low to avoid congestion on their cells where RBs are requested by the demand MNO. Meaning that it specifies (just as an example) if SUT in a cell is 70%, the supply MNO declines to share RBs of this cell, as by this threshold, this cell is considered as overloaded.

[2] This is a generic definition, so the impact of channel and correspondig parameters are considered and applied in the simulation setup section.

[3] The total received wide-band power (measure in all symbols) including the wanted power from the serving cell as well as all interfering cells and thermal noise and noise generated at the receiver, in the entire bandwidth [166]. Assume multi-cell single MNO in the downlink, with frequency reuse one, the received power at UE side from the serving BS (i.e., RSS) is wanted power, and the intracell interference is calculated from non-serving BSs (which all are attenuated by shadowing). So what we have at the beginning of each TTI is just wideband RSS from the serving BS (which is literally the transmit power of the serving BS) and the RSS values from other BS. Now the RSS of serving BS is degraded by RSS of other cells (known as interference).

$RSS_s^{BW_{own}}$ refferes to received power from the interfering BSs in the entire MNOs' network (with total number of N cells)[1]. The $\overline{\eta}$ is the noise floor over the entire bandwidth BW_{own}.

In the case of single MNO the SINR calculation is relatively straightforward, as there is one known serving BS, and multiple adjacent interfering cells. However, upon IOSS procedure, when a cell based on equation (3.2) is identified as a overloaded cell, when we reach to the status of SINR calculation, the amount of shared BW must be identified, and allocated to the demand MNO (it can be one RB or multiple RBs or even the entire BW from the supply MNO). Besides, the interfering cells must be recognised (from demand MNO to supply MNO and vice versa), and based on this the respective cells in supply MNO must evacuate the shared bands.

So, when the SS procedure begins, the metric in equation (3.3) must be modified to equation (3.5), as apart from the demand MNOs network, those cells from the supply MNO operating in the shared bands (excluding the cell(s) that have evacuated the RBs as requested) are considered as interfering cells.

It is worth to remind that the SINR estimation procedure should happen when the number of RBs that is shared as well as the interfering cells of the supply MNO already have been identified via the SS technique is employed. How accurately and efficiently these procedures, i.e., the SOP identification as well as identification of involved cells are done, depends on the efficiency of the SS technique/mechanism that is applied; whether is centralised? Sensing based? REM based? This is what we discuss in the rest of this Chapter.

Assuming only one cell requests for shared bandwidth, in the demand MNOs' network, the $SINR$ of UE_u at $time_t$ over the entire bandwidth with total number of

[1] For the multi-cell simulation there are two options: either to consider a threshold as of [165]which based on that we exclude those cells that the received power from them does not cause the received power from the serving cell to fall below the threshold. Or as of [167] we consider two rings surrounding the serving cell as an interfering cell. Subject that the threshold is accurate enough, the first option is less computationally complex. As of [165] the SINR threshold for identification of a BS as an interfering BS is set to 45dB.

$R_{Own+shared}$ RBs, is defined as follows:

$$SINR^{BW_{Own+shared}}_{u_{demandMNO},t,serv.} = \frac{RSS^{BW_{Own+shared}}_{serv.}}{\overline{\eta} + \sum_{\substack{s=1 \\ s \neq serv.}}^{N} RSS^{BW_{Own}}_{s} + \underbrace{\sum_{s=N+1, s \neq evq.}^{M} RSS^{BW_{shared}}_{s}}_{\text{Interference from all cells of the supply MNO}}} \tag{3.4}$$

Where $RSS^{BW_{Own+shared}}_{serv.}$ is the total received power from the serving BS over the own, plus the shared bandwidth, in the serving cell. The $RSS^{BW_{Own}}_{s}$ is the interference from each of the cells of the demand MNOs' network (over the own bandwidth). M refers to the number of cells in the supply MNOs' network, and section specified with under brace is the interference from all the cells of the supply MNOs' network (over the shared bandwidth) excluding the one(s)were identified by the sharing mechanism to evacuate the band, which in the equation (3.5) are denoted as $s = evq$. This interference is inevitable the same as single MNOs scenario where the interfering cells accorss the network affect the SINR of the SINR of the UE. However, if the SS technique fails to identify the $evq.$ cells correctly, we end up having these cells to affect the UE as follows:

$$SINR^{BW_{Own+shared}}_{u_{demandMNO},t,serv.} = \frac{RSS^{BW_{Own+shared}}_{serv.}}{\overline{\eta} + \sum_{\substack{s=1 \\ s \neq serv.}}^{N} RSS^{BW_{Own}}_{s} + \sum_{s=N+1, s \neq evq.}^{M} RSS^{BW_{shared}}_{s} + \underbrace{\sum_{s=evq.} RSS^{BW_{shared}}_{s}}_{\text{Interference from co-channel cell(s) supply MNO}}} \tag{3.5}$$

The section specified in red shows the interfering impact of evq. cell(s).

To identify the impact of SS on performance of the UEs in supply MNOs, from in the co-channel cells excluding the one(s) already have stopped operating/evacuated the shared bands, the $SINR$ of the UE, at any cell s where the cell is not required to be involved in SS (i.e., *evq.* cells), is defined as:

$$SINR_{t,s,u_{supplyMNO}^{BW_{Own}}} = \frac{RSS_s^{BW_{Own}}}{\overline{\eta} + \sum\limits_{\substack{s=N+1 \\ s \neq servingcellMNOsupply \\ s \neq evq.}}^{M} RSS_s^{BW_{Own}} + \sum\limits_{s=evq.} RSS_s^{BW_{Own-shared}} + \underbrace{RSS_{serv.MNO_{demand}}^{BW_{shared}}}_{\text{Interference from demand MNOs' serving cell}}} \tag{3.6}$$

In equation (3.6), is is shown that the cells are affected by the serving cell of the demand MNO operating on the shared bands which is denoted by $RSS_{serv.}^{BW_{shared}}$. However, this value as an inevitable part does not significantly affect the SINR value, as it is a substitution of the power of cell(s) termed *evq.* over the shared bands which already stopped transmission on the shared bands.

For the UEs inside the cell(s) termed *evq.* where the specific RBs should be evacuated, the SINR is calculated as follows.

$$SINR_{t,s,u_{supplyMNO}^{BW_{Own-Shared}}} = \frac{RSS_s^{BW_{Own-Shared}}}{\overline{\eta} + \sum\limits_{\substack{s=N+1 \\ s \neq servingcellMNOsupply.}}^{M} RSS_s^{BW_{Own-Shared}}} \tag{3.7}$$

The same as queation 3.5, if the *evq.* cell(s) are not identified accurately, we end up having the *evq* cells still operating in co-channel bands in parallel with the cell demand MNO. As a result the interference is induced to UEs of supply MNO, which is seen below (specified in red):

$$SINR_{t,s,u_{supplyMNO}^{BW_{Own}}} = \frac{RSS_s^{BW_{Own}}}{\overline{\eta} + \sum\limits_{\substack{s=N+1 \\ s \neq servingcellMNOsupply.}}^{M} RSS_s^{BW_{Own}} + \underbrace{RSS_{serv.MNO_{demand}}^{BW_{shared}}}_{\text{Interference from demand MNOs' serving cell}}} \tag{3.8}$$

The defined metric above are the critical metrics to investigate the impact of IOSS through various techniques on the performance of baseline LTE-A (i.e., equation (3.3)).

3.3.2 Problem formulation

In this section the IOSS problem is formulated considering equations (3.5, and 3.7). The overall objective is to maximize the total capacity (throughput[1] is considered here) of the demand MNO[2], while the interference level introduced in (3.5, and 3.8) and are highlighted in red, to the UEs remain equal/lower than the specified threshold (this threshold can be agreed and there is no already defined value for it).

$$\text{Maximise} \qquad Tput_{total,T}^{MNO_{demand}} = 1/N \sum_{s=1}^{N} \sum_{u=1}^{U} \sum_{r=1}^{R_{Own+shared}} \alpha_{r,t,s,u} Tput_{u,r,s,t} \tag{3.9}$$

$$\text{Subject to} \qquad I_{u_{MNO_{demand}}}^{ofMNO_{supply}} = \sum_{s=evq.SupplyMNO} RSS_s^{BW_{shared}} \leq \Theta_{th} \tag{3.10}$$

and

$$I_{u_{MNO_{supply}}}^{ofMNO_{demand}} = RSS_{serv.MNO_{demand}}^{BW_{shared}} \leq \Theta_{th} \tag{3.11}$$

$$\text{Where} \qquad \alpha_{r,t,s,u} \in 0, 1, \sum_{u=1}^{U} \alpha_{r,t,s,u} \leq 1 \tag{3.12}$$

Where U indicates the number of users, $R_{Own+shared}$ represents the number of RBs from the demand MNOs BW as well as the ones in the shared BW, and $\alpha_{r,t}$ is a

[1] Calculated from [162], as the total number of bits (Transport Block size is considered appying 10% BLER at the UE) transmitted over the entire simulation time for all the UEs. If system throughput is considered it is averaged over the total number of cells.

[2] Please note that, as stated earlier without loss of generality for the case of simplicity in simulation we only consider one directional sharing. However, the sharing agreement can be bidirectional so that both MNOs get benefit from SS, which this objective function is more fare for both MNOs.

coefficient that specifies binary allocation of RB_r to the UE_u at the $time_t$ in a cell. In 3.12 it is specified that each RB at each time can be allocated maximum to one UE. It is worth to point out that the optimal value for the I_{total} is *zero* (in linear scale).

In order to achieve the objective in 3.10, we need to satisfy the constraints in 3.11, and 3.12. The main challenge is to identify the SOPs and corresponding co-channel cells of supply MNO (that can evacuate the respective SOPs, or make sure they are not operating on the shared bands) efficiently. Without applying any coordination technique, the conditions in equations (3.10) and (3.11) are unlikely to be met, as there is no view of utilisation of the bandwidth in a RBs granularity level.

As discussed earlier, in large-scale networks (realistic deployment of mobile cellular networks), when frequency re-use is one, the overloaded cell of the demand MNO, should coordinate with all the cells of supply MNO which overlaps with, for interference-free SOP request. From the Figure 3.2, it can be observed that the demand cell, must either keep coordinating with multiple cells for a part of bandwidth which is not utilised in that cells (which is unlikely [33]), or avoid the utilisation of shared spectrum in the cell edges (which limits the freedom of utilisation of shared bandwidth). The currently available ICIC mitigation techniques in single MNO scenarios, such as CoMP, cannot help this problem[1]. Here, the application of REM[2] is investigated for the two mentioned topologies, and that how it helps to solve the multi-cell SOP awareness and meet this threshold limit (i.e., Θ_{th}).

[1]It is worth pointing out that the enhancement of CoMP/ICIC between the MNOs may further improve the performance of the IOSS, however, consideration of this issue is beyond the scope of the thesis.

[2]It is reminded that the impact of applying SOTA of REM in IOSS is considered in this Chapter. Thus, the enhancement of currently available REM techniques, is not the focus of this Chapter.

3.3.3 Underlying REM Model, Assumptions, and Dissemination for IOSS

The REM is presented as a map of the RSS values in a finite $\mathbb{R}^2$ space[1] for a bandwidth of interest BW with R number of RBs (with the RB level frequency granularity), and time granularity of t. More precisely, in the Region of Interest (ROI), which is the mobile cellular network (of two co-existing MNOs), V (any type) total number of sensing capable devices (fixed and wide-band capable sensors in this thesis[2]) are assumed to be evenly distributed following a regular square grid-based layout, with the equal distance d to perform ED. The reason for grid layout is to have more control over the network in a smaller scale. To reduce complexity of simulation, it is assumed the network is full of scatterers, so sensors and the UEs face uncorrelated shadowing.

The constructed REM environment is depicted in Figure 4.1. Grid sizes are specified based on the communication system range (in terms of power). So the grid size of 250m is setas of [168] and [169]. For short range systems such as DECT and WLAN grid size 15m is considered vs for mid range technologies such as Digital Video Broadcasting-Terrestrial (DVB-T), Global System for Mobile (GSM), Universal Mobile Telecommunications System (UMTS), and LTE, grid size is specified as 250m. The mobile cellular networks can be considered as mid-range power. Assuming the location of sensor nodes is known, sensors collect the RSS[3] values (over the frequencies that carry data and not the control information) and forward to the Spectrum Broker along with their corresponding geolocation information, resulting in spatial awareness of SOPs. As the number of sensors must be kept minimum across the network (due to the cost of de-

[1] A 3-D map (with $Height_H$, $Width_W$, $length_L$) is an ideal approach, but to reduce the computational complexity by H, i.e., from $W * L * H$ to $W * L$, a 2-D map is constructed, assuming UEs and sensors are located on a same surface.

[2] Subject to accurate localisation, the static UEs instead of sensors can be assigned to contribute in REM construction, however, as the location of UEs varies if mobility is modelled, varying localisation of measurements will be computationally complex in simulations.

[3] Power Spectral Density is measured on a RB level basis, as of [165] assuming the downlink power from each BS is evenly distributed across the entire bandwidth.

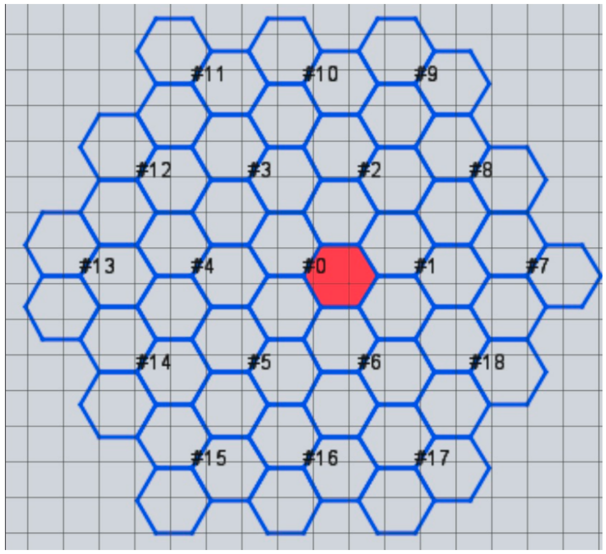


Figure 3.3: Constructed REM Environment

ployment[1], mid-range capable sensors are assumed[2], with medium density is applied. A Kriging-based interpolation technique is exploited, to cover the locations that the sensing results are not available, to have a complete overview of SOPs in the entire network. However, at lower densities of sensors the interpolation error dominates, a margin for this error is considered.

To take the temporal awareness of SOPs into account, the statics of observations (sensing rate) is set to time granularity of t. This periodic sensing time frame may vary based on the characteristics of the systems. For instance, the SOPs vary every TTI (i.e., 1ms) in the LTE-A. Hence, to avoid the outdated observations, the t must be set compliant with LTE-A air-interface time frame, which is every 1ms (this can be assumed static within each 1ms). For the measurements, the perfect sensing is assumed, and the imperfections (e.g., hidden node problem, slow sensing time, etc.)[3] are not detailed. However, two important points are taken into account. First, for a bursty and very

[1] As of SOTA REM, there is a trade-off between the sensing capability (spatial diversity gain) and the density of sensors (number of sensors required).

[2] Sensing range in dB, (or RSS) at the receiver over particular BW is calculated as: Pinput (dBm) – Pnoisefloor(dBm).

[3] Other imperfections such as SNR wall (imperfect knowledge of noise power level, leads to estimated level of noise differs from actual noise power) is also assumed negligible.

short duty cycle (1ms level) there is a high chance of miss detection. The second point is the noise uncertainty which causes false alarm. To consider the impact of false alarm due to noise and miss detection due to low duty cycles, only those samples above the detection threshold for averaging and spatial modelling is considered. The threshold is set to $-105dBm/180$ kHz as reasonable trade-off between probability of false alarms as of [168], triggered by strong noise samples, and the probability of missed detections of bursty signals.

Even though fast sensing is assumed in this work, considering the required time for the transmission of the measured data to the broker, in LTE-A architecture might be ambitious to have sub-frame level broker update rate λ (i.e., REM update rate). Although the average delay for the CQI feedback report is 5ms in LTE-A (set in simulation section) the REM update rate needs to be in 1ms basis in real-world deployment with an realistic interface. The REM information can be static (e.g., terrain features,) or dynamic (e.g., spectrum usage patterns, location of transmitters and receivers, propagation, up-to-date RSS measurements). The overall delay for REM information from measurement procedure until it reaches the final destination, consist of; RSS measurement delay, processing delay, queuing delay, and transmission delay. Delay can affect the freshness and utility of dynamic REM information as outdated information for real-time adaptation can be useless if the dissemination delay is too big. With regards to REM transmission, the REM can be disseminated through a dedicated control channel and fast interface. Regarding the RSS measurement, delay is very much dependant on the capability of the sensors, and the frequency range a sensor can monitor at any given time which is limited by its maximum sampling rate and any intermediate frequency filters. Moreover, some other factors, such as the distance between sensors and fusion center matters.

In this thesis, which is a feasibility study of REM for LSA and IOSS to obtain a baseline knowledge of its impact on performance of static scenario of mobile cellular system (i.e., with no mobility and less dynamic), the assumption is the sensors and interfaces are perfect, and thus, the delay as a result of these factors are assumed negligible. The delay associated with the computational complexity of the information processing (when RSS already sensed/measured and sent to the fusion center for processing to interpolate and create the map) is considered and discussed later in this Chapter. However, the overall value for the actual delay will be considered/measured when this approach is evaluated in testbed and real-world environment [170], [171]. Besides, upon IOSS procedure, for the shared spectrum request, allocation, as well as the band evacuation procedures, an additional time should be specified[1].

Assuming uni-directional SS (without loss of generality, and just for the purpose of simulation simplifications), every 1ms, the RSS values from all the downlink BSs in the MNO supplys network, and over its entire BW but per RB, at the each sensors location is considered as REM data. The data is then sent to the broker. The RSS values are compared to the threshold to make binary decision regarding the occupancy status of the RBs at the location of sensors. We review the steps for one square grid and this can be generalised for the entire network.

In a square grid of interest, for any sensor k_i at location (x_{k_i}, y_{k_i}) thatnomenclature[S]KREM data set from measurements performs measurement, over the R number of RB, the RSS value can be calculated from the equation 3.13:

$$Z_{k_i,RB_r}(x_{k_i}, y_{k_i}) = \begin{cases} \sum_{s=N+1,s\neq evq.}^{M} (RSS_{RB_r}^{SharedBW} - L - SH - FF) & \text{if RB} \\ \text{is occupied, and is detected} & \\ Null & \text{otherwise} \end{cases} \tag{3.13}$$

where L [2], is pathloss and represents impact of power loss as a function of distance,

[1] In the LTE-A, Cell-specific Reference Signal (CRS) is transmitted over the entire bandwidth (i.e., all the RBs, but specific Resource Elements,) in all sub-frames [162]. The positioning of these signals varies in adjacent cells to avoid interference for correct cell-ID detection (time or frequency offset depending on the duplex mode). Thus, it is important for the REM entity to be aware of this positioning, and upon sharing inform the supply MNO to stop transmission of these signals over the shared spectrum in corresponding cells.

[2] For LTE-A simulation setup please refer to the A.1

SH represents macro scale fading (shadowing), and FF represents microscale fading (flat fading here)[1]. From(3.13) assuming n sensors are involved in the square grid of interest, the set of RSS measurements per RB_r is modelled as the realisation of the observation vector (3.14).

$$K_{RB_r} = [(Z_{k_1,RB_r}, ..., Z_{k_n,RB_r}] \tag{3.14}$$

For the locations where sensors are not available the RSS values at any arbitrary point p, at location (x_p, y_p) for RB_r inside the square grid, are estimated using kriging-based spatial interpolation technique in conjunction with the measured datasets in 3.14. The algorithm calculates the spatial correlation between the measurment sample and the optimal weighting coefficients for the 3.15 for the measured values while calculating the approximated value in the target $location_p$. More information about Kriging technique can be found in [172], and all the references therein.

$$Z_{p,RB_r}(x_p, y_p) = \sum_{k=1}^{n} w_{ki} K \tag{3.15}$$

The REM construction procedure is summarised in Algorithm 1.

This mechanism can be generalised to create SOP binary values for the entire network geometry which are updated every 1ms. When the map is created for the ROI (entire network), upon request (see Figure 3.4) any cell of demand MNO can ask for available shared RBs, specifying the location where the shared RBs are needed. REM identifies respective overlapping cells of supply MNO with the demand cell and the SOPS can be allocated without concern of interfering the co-channel overlapped cells. Now the SINR values discussed in equation 3.5 and 3.8 can be calculated as the overlapped cells have been identified. The flow of general IOSS procedure is depicted in Figure 3.4.

Although the optimal value of I is zero for the 100% interference protection of both

[1]In real-world environment the real sensing capable devices perform sensing method such as ED, and FFT. Here, for the purpose of simulation all the measurements are modelled/estimated via typical propagation/pathloss models.

Algorithm 1: REM Construction Algorithm

Data: Set of sensors/data points K = {k_i} i=1,…,n
Data: Target point p at location (x_p , y_p)
Data: Power spectral density Z(k_i) of data point at location (x_{ki}, y_{ki}) on RB_r
Result: Estimated power spectral density Z_p in a location (x_p, y_p) for each RB_r
K ← ∅
for all RB_r do
  for all data points in the set k_i do
   Estimate Z(k_i)
    K ← K ∪ {Z(ki)}
    return K
  interpolate K
 Return Z_p
end
end

supply and demand MNOs, a value of -85dBm/10MHz (-102dBm/180KHz) [10] is considered as a tolerable interference threshold[1] to compare with results of REM. The Effectiveness of this approach is evaluated in the next section.

3.3.4 Performance Evaluation and Analysis

As mentioned earlier for the simulation two MNOs with two distinctive co-existence topologies are implemented, with 57 cells each. The UEs start their session randomly but within 33ms of initial simulation. This represents variable transmission time for each UE (temporal variation in RB utilisation from traffic side) are randomly distributed across the each cell[2], but uneven across the network to model overload cells (variable spatial RB utilisation). The Vienna system level simulator is exploited for this first part of simulation. To reduce complexity of simulation, low density of UEs is simulated, however, to generate enough data to congest some cells for the purpose of IOSS investigation, high data-rate($1920 * 1088$ pixel resolution [173]) real-time Video streaming traffic (bit streams with average data rate 2.84Mbit/s) are created using H.264/AVC codec [174] with frame rate 24fps, for the entire simulation time 67000ms.

[1] This value is quite conservative to reduce risk interference on the actual owner of the license (of the spectrum), and reduces the gain of SS. However, as there is no confirmed/standard value for this threshold, in this research we follow [10].

[2] The Number of UEs in each cell is discrete uniform random variable. The UEs arrival time, and the UEs distribution across the cells follow uniform distribution.

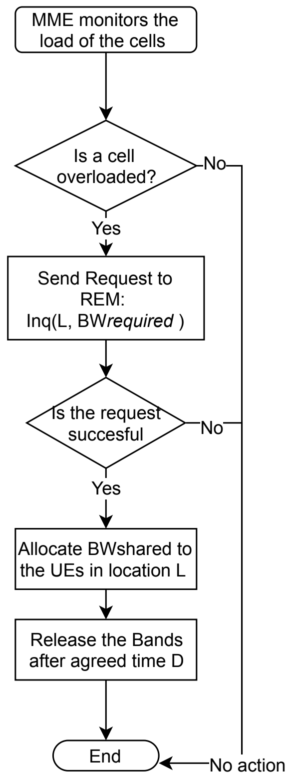


Figure 3.4: Flowchart of the pre and post processing REM-Based IOSS procedure

For the second part, the generated data as an input for the implementation of REM approach is exploited. More information regarding the simulation parameters are shown in individual Tables for MNOs deployment (in Appendix 1), and REM in Table 3.1. In order to achieve statistical accuracy, 25 simulation runs were executed. In each case, the 95% Confidence Intervals (CI) are depicted in the form of error bars. The performance is compared to the baseline LTE-A, [33], and [34] (for the rest of the discussion below the are indicated as: REM-enabled, SOTA, centralised, and sensing based respectively).

3.3.5 Simulation Results

Earlier we discussed SOTA (centralised, and sensing based) approaches, and that how REM-based approach performs differently. Before we start to investigate empirical

Table 3.1: REM Simulation Setup

REM attributes and Simulation parameters for REM construction	
REM ROI	3.5km * 4.0 km = 14km2 (19-site, hex-grid layout the inter-site distance with 750m)
Sensors placement	regular square grid of size 250 m×250 m (total 224 square grids)
dataset	PSD Correspond to the LTE RSS over 2GHz, BW=10MHZ, 50RBs
Update rate	1ms intervals
Sensing range	-105dBm/180KHz
Number of Sensors in entire network	896 (4 per square grid) with equal distance (evenly distributed)
RB experienced by sensors	3GPP 36.942 Urban Pathloss model, Rayleigh distribute Fast Fading, Log normal shadowing (correlated shadowing is not modelled)
UE numbers	Min=5, Max=10 with uniform distribution
Noise figure at sensor side	sensor zero mean Gaussian noise with variance 3 dB added to the measurements

results of REM-based approach and comparison with SOTA approaches, we present a high level snapshot from output of REM and compare it with the output of centralised an sensing based approach. These snapshots give us a generic overview of how each method captures SOPs, i.e., the dimensions the SOPs are captured (temporal/spectral, or temporal/spatial/spectral).

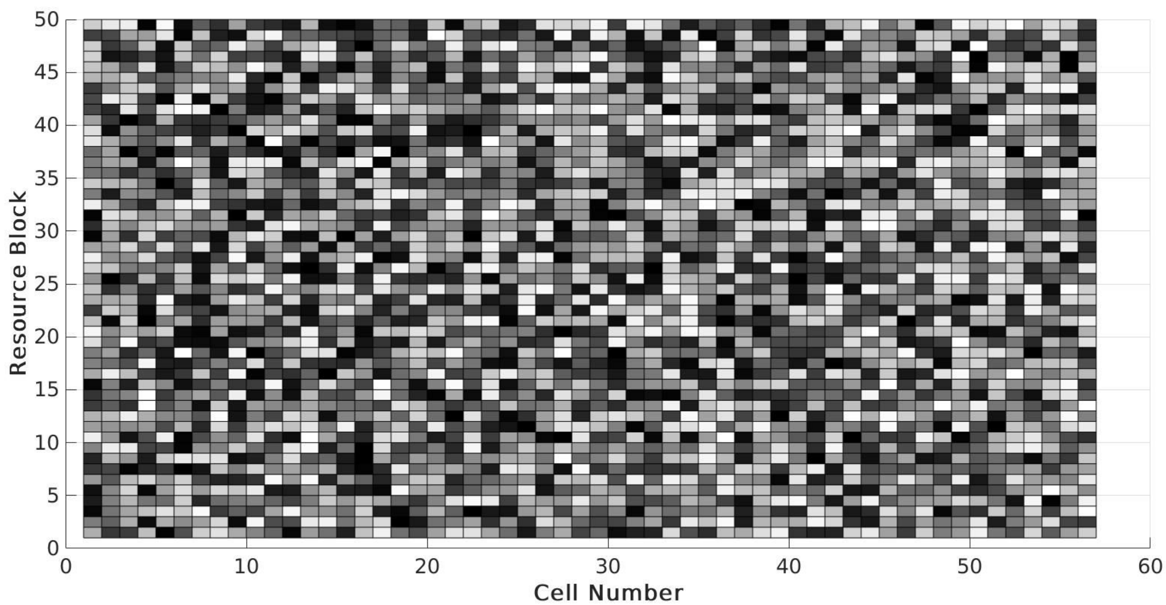


Figure 3.5: SOP snapshof from Centralised-based IOSS

The snapshots have been captured at a random simulation time t (400ms of simulation duration) and are presented in Figures 3.5 and 3.6. Figure 3.5 shows how centralised

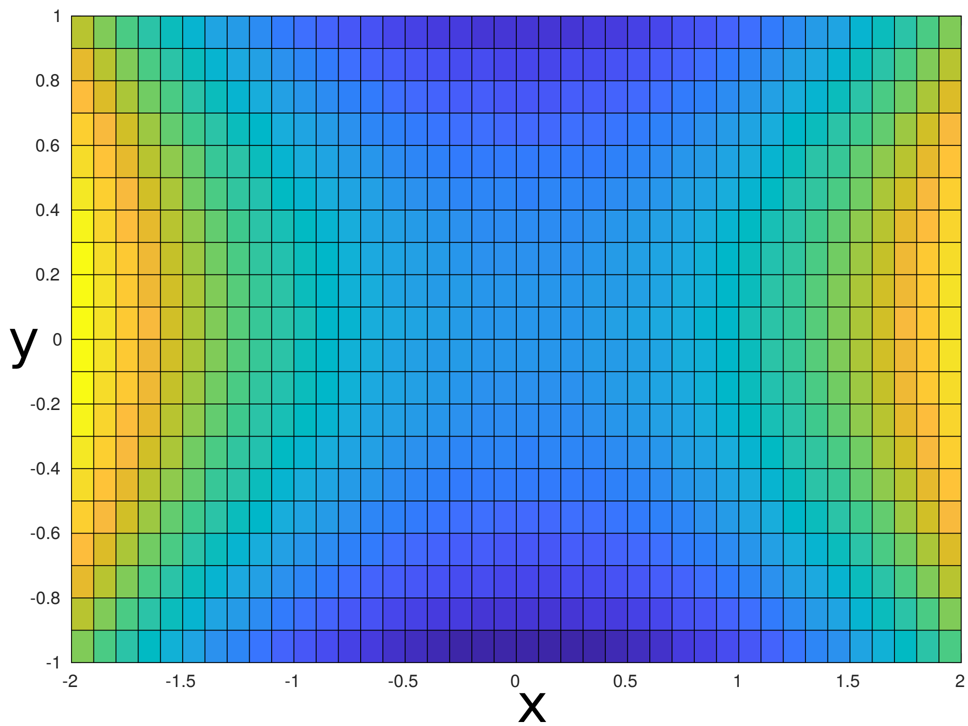


Figure 3.6: SOP snapshot from REM-based IOSS. The distribution of power as a function of distance (in meter) at each location (X,Y) in 2D plane.

approach provides map of 50 RBs occupancy for 57 cells of one MNO. The squares in black represent occupied and the ones in white represent unoccupied RBs (other colors represent control information, as not necessarily all resources are dedicatedly for data). Based on this figure we can see that the RB utilisation has been captured in time and frequency domain, i.e., temporal/spectral. Figure 3.6 shows a heatmap view of the distribution of power over on RB at time t at different locations, as result of applying REM. More precisely, this figure depicts distribution of transmit power over one RB r and time t as a function of distance in a Cartesian plane (location/points are specified with X and Y) which represents 2-dimensional map from spatial point of view. The areas are specified in yellow represent the RB r is occupied, and in further distances which are specified in blue, represent the SOPs. Thus, we can see through REM-enabled approach we can obtain temporal/spatial/spectral overview of SOPs over the network.

In the following subsection, we evaluate the performance of REM-based IOSS, based on simulation, considering simulation parameters and system model already discussed.

The performance is compared with baseline LTE-A, centralised , and sensing based approaches. With regards to the topologies of two MNOs with respect to each other, some of the results are presented for both co-located and non-collated topologies individually. It is worthwhile to remind that as a result of SS we are after increasing the number of RBs by using shared RBs to entail an increase in system/cell/UEs throughput for the demand MNO. This performance improvement allows either higher quality in video transmission, which implies higher data-rate, or accommodating a larger number of UEs. Besides, we evaluate the impact of SS on performance of the supply MNO to show whether this approach does not degrade the performance of supply MNO. Moreover, SUE as a generic metric is defined to show how REM-based approach has contributed to increasing this important factor.

Collocated Deployment

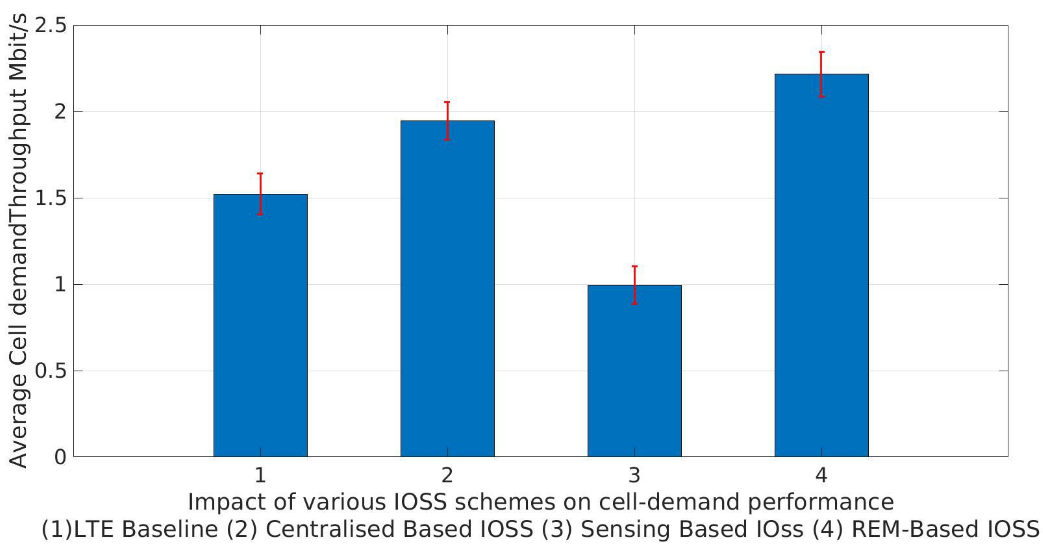


Figure 3.7: Impact of various IOSS schemes on cell-demand performance

In Figure 3.7, the average throughput for one demand cell is depecited from LTE-A baseline (as non-sharing), centralised, sensing, and REM based SS. It can be observed that the centralised approach, does not provide considerable gain due to its conservative shared SOP allocation [33] and only temporal/spectral awareness of SOP maps, as we discussed comprehensively. The sensing based approach, offers the worst performance, as the sensing is not cooperative, a conservative interference threshold (mentioned before) is considered to identify any RB as free, more specifically in the cell boundaries. The REM-based approach captures SOPs in a cooperative was, with overview of SOPs in spatial/temporal/spectral dimensions. Assuming the REM-update rate is plausible in real-time (1ms), the REM-enabled approach increases the cell throughput in the demand cell by without any performance degradation on the supply MNOs' network which calculated in (3.8), and is shown and discussed in the following figures.

The impact of these IOSS schemes is observed from the supply MNOs perspective, and depicted in Figures 3.8, and 3.9. The centralised based approach performs well, as a result of its conservative interference avoidance mechanism (all the adjacent cells must stop operation on the same set of RBs which are allocated for sharing to the demand MNO). The sensing based approach fails to capture potential interference fields, resulting in lower SINR, compare to the case no SS is applied, when multi-cell is deployed. REM-enabled approach, however, performs far better to capture interference areas by avoiding allocation of RBs to the demand MNO. The REM-based approach has resulted almost the same as baseline LTE-A and centralised approach which means it does not degrade the performance of the LTE-A.

Non-Collocated Deployment

The same investigation is performed for the non-collocated deployment scenario.In the 3.10, the cell throughput for the demand cell as a result of various SS mechanism compared to the baseline LTE-A is shown. It is observed that REM-based approach follows almost the same performance compared to the collocated scenario. However, due to the conservative sharing condition, the gain is almost 0% (it is shown in the figure where the throughput LTE and centralised approach is almost the same). For sensing based approach also there is slightly lower gain compared to the collocated scenario as the demand cell overlaps with multiple cell of supply MNO, and it is no capable of

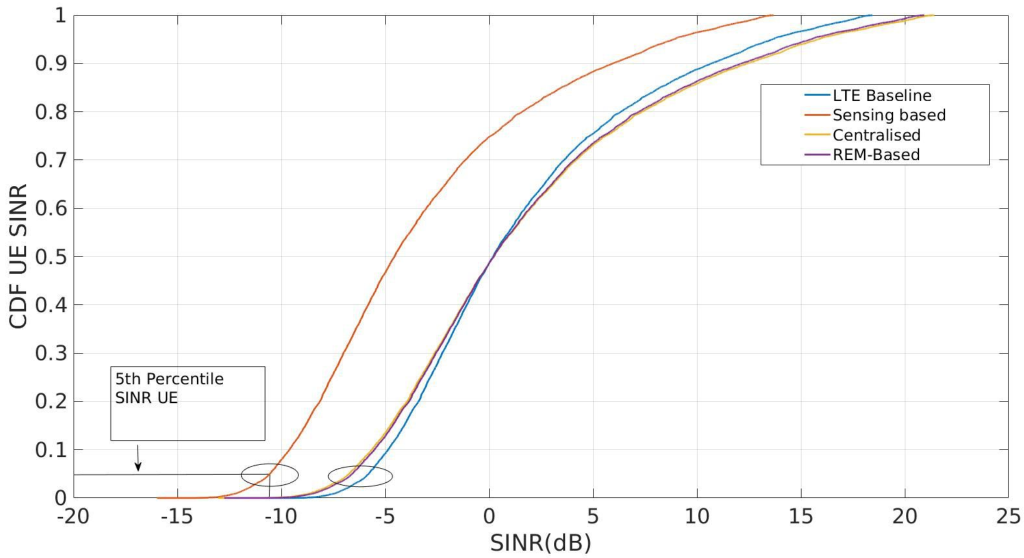


Figure 3.8: Impact of IOSS on UE SINR of the Supply MNOs network

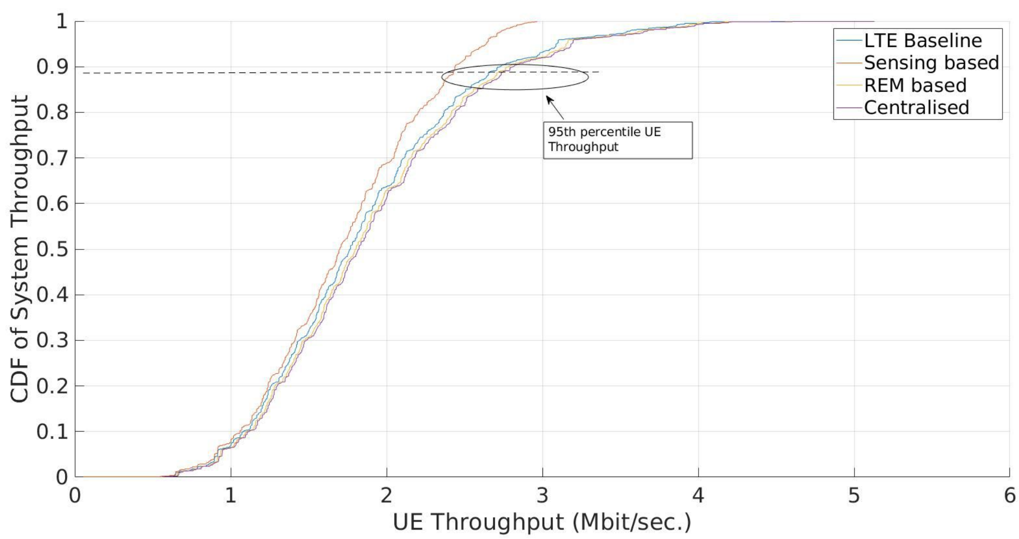


Figure 3.9: Impact of IOSS on Throughput of the Supply MNOs UEs

accurately detecting SOPs specifically at cell edges .

The figures 3.11, 3.12, show impact of SS on the total cells in supply MNOs. We see that the centralised based approach does not degrade the performance of LTE-A, as it does not allocate any RBs to the demand MNO, in the case the RBs can not be released in the adjacent/overlapped cells. The sensing based-approach performs worse

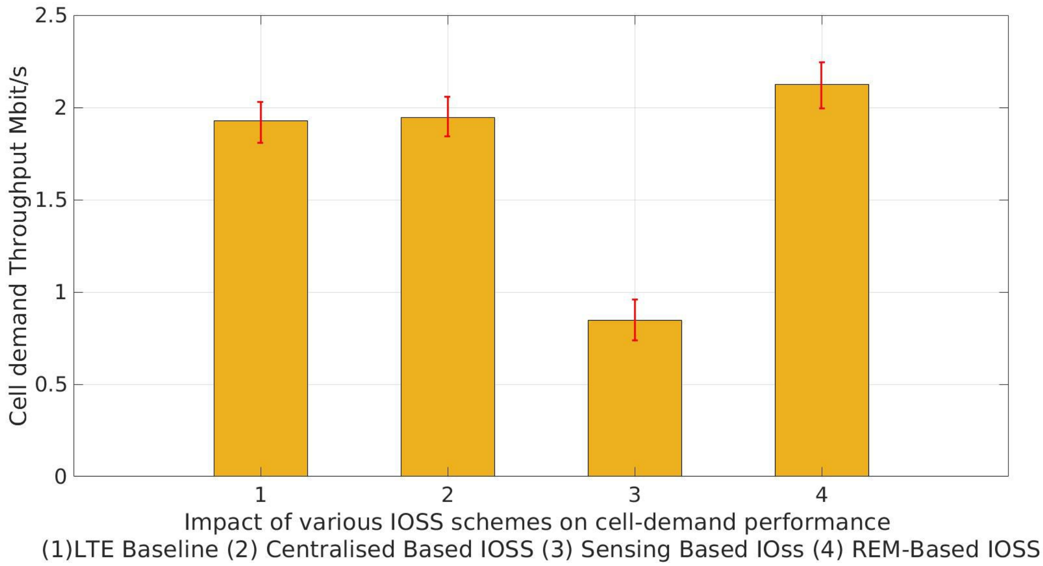


Figure 3.10: Impact of various IOSS schemes in cell demand performance (Throughput)

than the collocated scenario, as it does not coordinated with all the adjacent cells (of supply MNO). The performance of REM-based approach is invariant as it performs at square grid level irrespective of location of the cells/MNOs to each other.

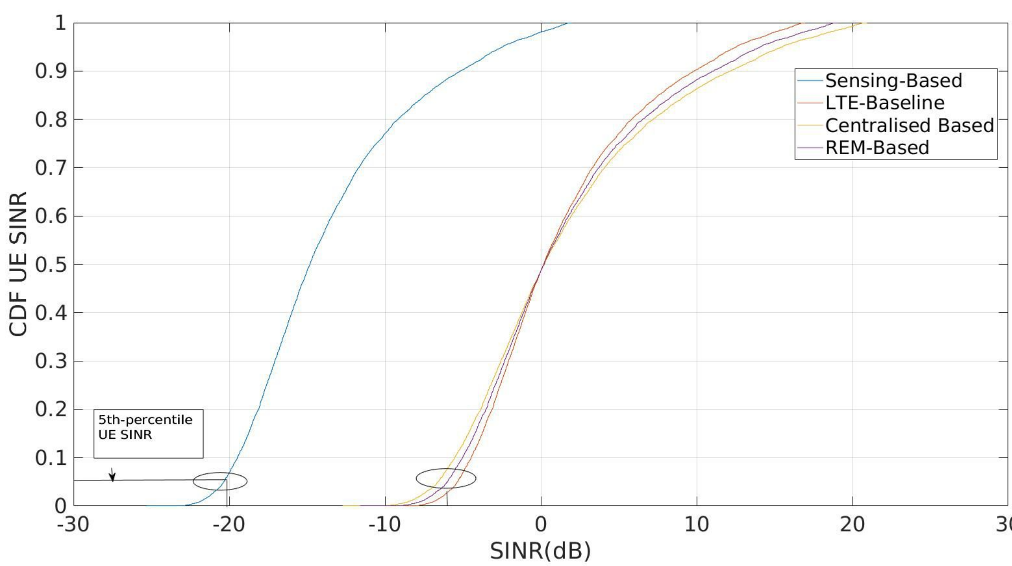


Figure 3.11: Impact of IOSS on UE SINR of the Supply MNOs network

The overall system throughput as a gain of SS for the entire MNO demands network (where multiple cells are overloaded) is presented in Figure 3.13, and 3.14 for collocated

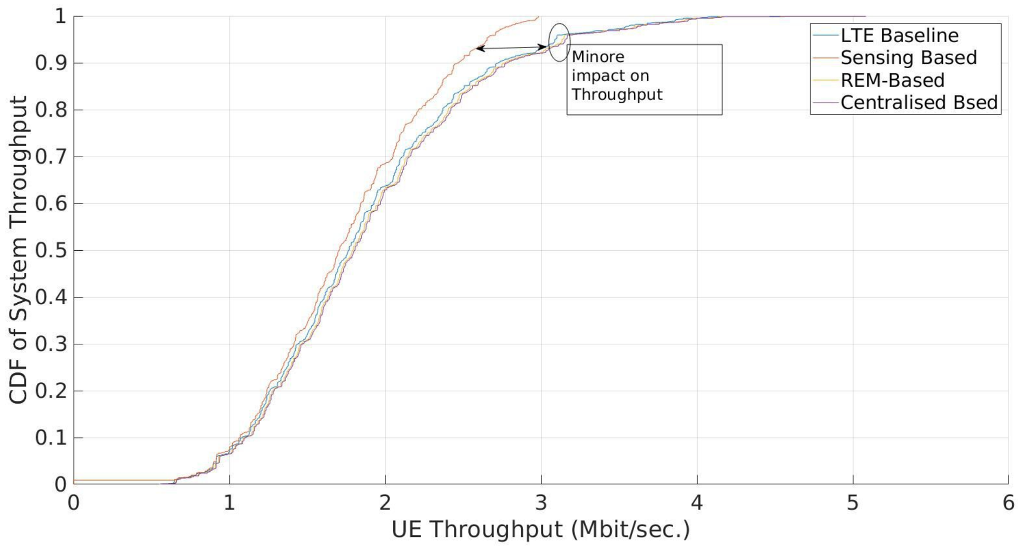


Figure 3.12: Impact of IOSS on Throughput of the Supply MNOs UEs

and non-collocated scenarios respectively.

In Figure 3.13 it is shown that REM-based approach provides higher gain compared to the centralised approach. Please note that, as discussed earlier we have considered a quite conservative threshold for interference protection which reduces the gain.

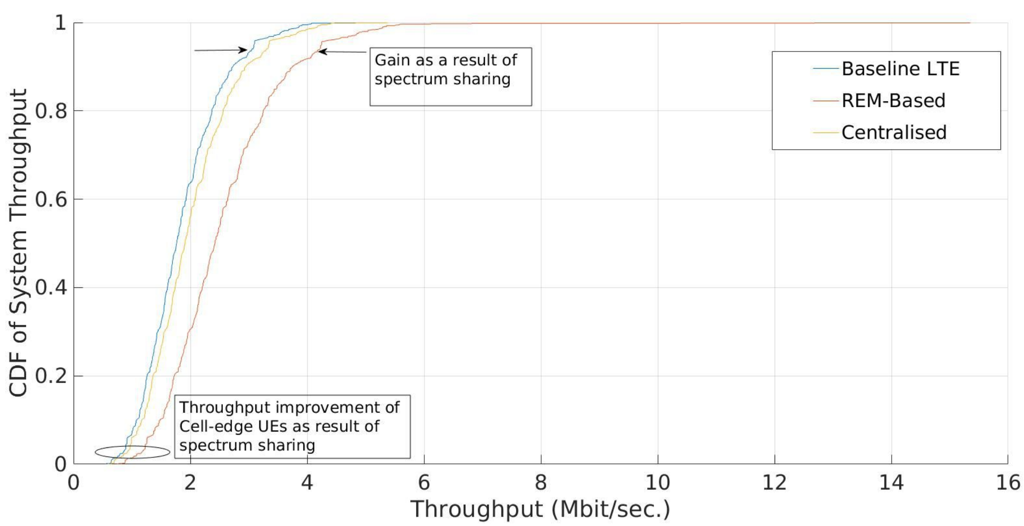


Figure 3.13: Collocated

In Figure 3.14 it is shown that REM-based approach provides higher gain compared to the centralised approach. The overall performance for both scenarios are preety much the same for REM as the SOPs are captured considering area of interest and not in a cell level.

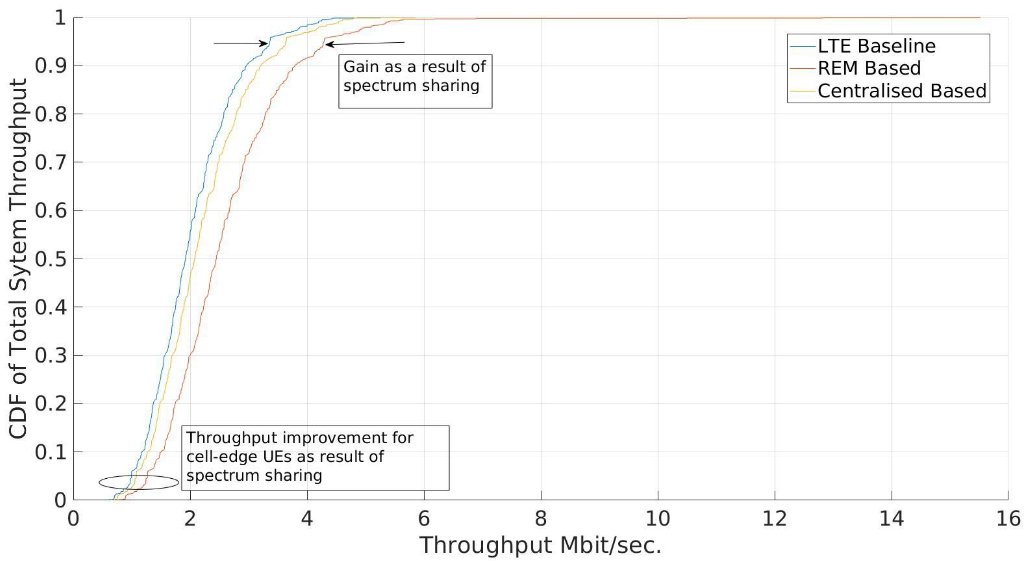


Figure 3.14: Non-collocated

Back in our early discussion about underutilisation of spectrum in sub-6GHz bands and the need for SS, we define the following metric to identify how much SS helps to improve utilisation of the spectrum. This metric only represents utilisation of spectrum in the entire system, and is calculated per cell for the entire number of RBs (BW) during observation time, and averaged over the number of cells. In other words it is a unit-less metric that shows percentage of RBs/BW/spectrum that has been utilised which is defined below:

$$S\bar{U}E_{BW}^{MNO} = \frac{1}{N}(\sum_{s=1}^{N}(\frac{\sum_{t=1}^{T}\alpha_{r,t}}{R})) * 100 \qquad where \quad \alpha_{r,t} \in 0,1 \quad r = 1, ..., R \tag{3.16}$$

Where $\alpha_{r,t}$ is a binary value subject to utilisation of the RB_r at $time_t$. This value is calculated for the entire system and averaged over the cells,as a metric to identify the efficiency of the systems.

A comparison of results is depicted in Figure 3.15 . It can be observed that REM-enabled IOSS significantly results in improvement of SUE, as compared to the case no SS is applied.

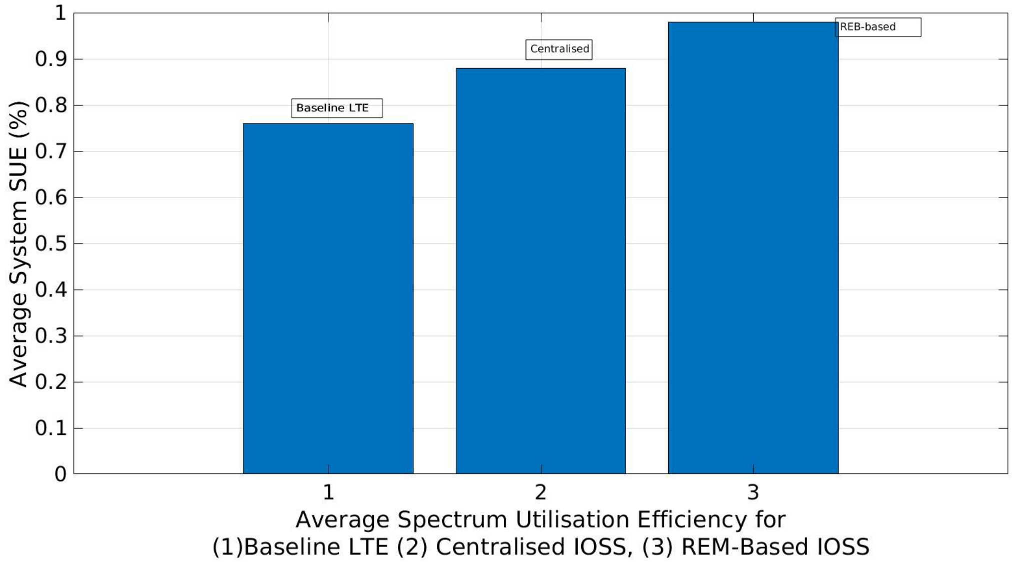


Figure 3.15: REM-based SUE gain with respect to the LTE-A Baseline and Centralised IOSS

3.3.6 Latency and Service Disruption Constraints

To evaluate the performance of REM-enabled approach on Video traffic quality, Packet Drop Rate[1], and Goodput[2] based on equation 3.17 results are calculated from the application level and compared to the baseline LTE-A. It is observed that through the REM-enabled IOSS, the high data rate traffic, can be accommodated (due to more availability of SOPs) with respect to the case of no SS. The latency is negligible as the algorithmic complexity of this approach for the static scenario is low (in real-world environments is expected to be lower, as real measurements performed) 3.16. It is reminded that this is subject to real-time update of REM approach with reasonable speed interface/link. However, this approach must be evaluated for the scenario in

[1]The total number of packets which are lost due to delay in the queue because of congested cell.
[2]The total number of useful bits excluding protocol overheads reaches at the receiver on time.

which the UEs have mobility with fast spatial variation (depending on the speed).

$$Goodput_{UE} = \frac{X_{useful} - X_{Overhead}}{T} \quad bit/s \tag{3.17}$$

Where X_{useful} represents total number of useful bits, and $X_{Overhead}$ represents total number of protocol overhead bits (specified in LTE simulation parameters table).

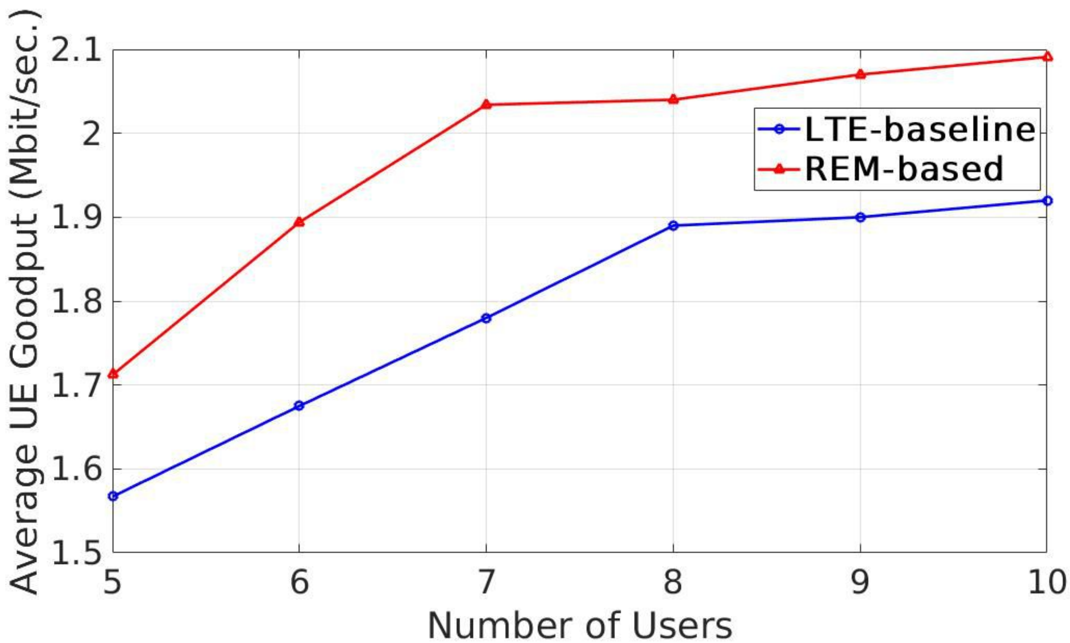


Figure 3.16: Goodput

3.3.7 Overhead Constraints

The amount of overhead due to deployment of REM is very much dependent on how it is deployed and the characteristics of environment (i.e., how static or dynamic the environmet is) that changes the RSS values. In some cases, there is no need to disseminate the entire REM, and only it is needed to update partial REM information that changed over the last update, which will reduce the overhead. However, in general there are basic number of infomertion (in bits) is tranmitted over the network (from sesors to the REM). Assuming BW with R number of RBs, then the number of bits for RSS value (interger value which is converted to binary of 7bits) and RB occupancy status (0 or 1) will be 8 (equals to $1byte$) which is transmitted from each sensor to REM. Another 16bits are considered as header with fixed information icluding the RB and sensor index (the header may vary for different REM deployments and number of RBs and sensors, more bits might be needed). Thus, the overhead at each 1ms for each sensor equals to $R * (8 + 16)$ subject that location of sensors are known in advance. In this thesis where 50 RBs from sharing is considered, the overhead per 1ms per sensor is $50 * 24/1ms = 0.12Mbit/s$. Please note that this value can be reduced with increasing the update rate where applicable [175], [171], and [176].

3.3.8 Impact of Traffic Correlation of MNOs on REM-based IOSS

From the SOTA of IOSS, there is considerable amount of work that evaluate the performance of IOSS as function of load of the involved cells. However, in this thesis it is realised that, efficient SOP awareness can not be achieved through the coordination with one cell only. The main difference between [33], and REM approach is that, in [33] the correlation is measured on a cell level. However, in REM spatial distribution of the load mattress, and correlation of one demand cell and one supply cell does not make sense, and mainly the spatial distribution of load (area of interest) matters. As RSS values are measured per RBs in any area of interest, there might be a case where the load of one supply cell is distributed in a specific part of a cell (special event is happening), and again spatial wise, rest of the cell is empty/less loaded. Based on REM the SOP map on the less loaded part of the cell shows opportunities for sharing. So there can/might be more SOP compare to the centralised based approach. However, as only one BS can transmit over particular band at a time (power is distributed across the entire cell), the SOPs might be more suitable for Uplink.

3.4 Summary and Discussion

The IOSS implemented and analysed for two distinctive topologies of the MNOs (LTE-A platform). The IOSS formulated and a novel mechanism termed REM-Enabled IOSS to address this problem was proposed. It was shown that the proposed approach which exploits spatial and temporal SUT information across the large-scale mobile cellular networks outperforms the SOTA approaches namely Centralised based IOSS and sensing based IOSS. In both deployment topologies REM-based approach achieves better gain in terms of average system throughput of 37.5% with lower negative impact on the performance of the supply MNOs' network. In Figure 3.13, collocated topology, it can be seen that the 95-th percentile (pointed with arrows), for baseline LTE is roughly 3 Mbit/s, and for the REM-based approach is almost 4.1 Mbit/s, which shows around 37.5% improvement in throughput. In Figure 3.14, non-collocated topology, 95-th percentile (pointed with arrows), for baseline LTE is roughly 3.2 Mbit/s and for the REM based approach is almost 4.3 Mbit/s. Thus the throughput improvement is around 36%. Most importantly SUE significantly is improved through this approach by 67% for a cell and by 23% for entire system (from baseline 75% in LTE-A[1] to 98% in REM based approach, shown in Figure 3.15). Moreover, the results were compared to the LTE-A baseline when no SS is applied. However, there are important points to note about the deployment of REM-based approach in LTE-A which are highlighted below:

Due to the nature of air-interface, the time granularity (resource scheduling and RB allocation varies every TTI) the performance of this approach is dominated by the fast varying SOPs in the time domain, meaning that the observation have to be updated every 1ms. In this context, in the areas that there is no UE of supply MNO for some time the measured RSS values will be invariant (below the threshold as there is no data transmission). However, the areas that the UEs are distributed, even though with no mobility, and fixed sensors are used the update rate needs to be conducted in 1ms time intervals. Adding mobility to the UEs, it makes the procedure more dynamic and challenging (location wise), as is likely that at any location in the cell, there will be a new transmission. The second point is the that, this approach requires the MNOs to provide their request for shared spectrum as well as the location of the SOPs is required.

[1]Please note that these values are obtained from the simulation scenario that was implemented in this thesis and is scenario and load dependant, and there is no specific standard value for it

Thus, adopting high resolution localisation of the UEs improves the performance and accuracy of REM-based IOSS.

Without this approach IOSS is impossible, unless the SOPs are guaranteed to be available for long term. It is expected that this approach will be a potential scheme that contributes to real-time allocation of the RBs to the MNOs, rather long-term assignment.

Another important and realistic fact is that the traffic across multiple MNOs could be correlated and interdependent. Thus, long term and frequent occurrence for shared spectrum may require for cell planning, as assuming the MNOs always have spectrum to share is not a valid assumption. Due to this reason in the next Chapter LSA is investigated applying the same approach. LSA compares to the IOSS provides wider bandwidth.

Chapter 4

REM-Enabled Licensed Shared Access

In this Chapter a novel REM-based LSA mechanism between the Mobile cellular network and an arbitrary LSA incumbent is proposed. It is shown that the proposed SS mechanism can provide better performance compared with the conventional approache with respect to [119].

4.1 Introduction

As discussed in Chapter 2, the LSA scheme has been investigated through various approaches so far. Initially, experimental live field trials carried out, in compliance with the standard reference LSA architecture [136], resulted in a time/location limited SOP awareness, and subject to immediate evacuation of the shared spectrum by the cellular network, when an incumbent user arrives (which is informed through assumed low latency and reliable interfaces) [137]. In most recent work, the interference imposed by the cellular network is approximated through the statistical propagation models, considering a predefined interference threshold to identify the potential interfering radius. The downside of the propagation-based approaches is that, unlike mobile cellular networks, not much information (i.e., actual radioelectric parameters, such as antenna height, terrain based or over the air, etc.) from the incumbent user is known, and therefore, no proper propagation pattern is modelled so far. The lack of accurate propagation model between the incumbent and cellular networks' transmitters, has resulted in applying conservative propagation models to estimate a worst-case scenario of interfering signal. Moreover, these methods do not identify the exact overlap area of incumbent with cellular networks. Thus, even though the presence of the incumbent is informed through an interface to the MNO, a wide coverage area of cellular network is identified as an interference zone (even though the incumbent overlaps only with part of the cells). This method is even more challenging in the LTE-uplink transmission mode, as the position of users changes over time due to user mobility and environmental factors, so the interference varies over time. The propagation-based approaches resulted in estimation result of widely overlap between the mobile cellular and the incumbent networks, making LSA scheme almost inefficient (or only applicable subject to long-term/spatial available SOPs). These motivates to explore the problem from a different perspective. More precisely, in this Chapter application of REM technique to the LSA is investigated , which in contrast to the SOTA of LSA, is combination of; sensing, statistical interpolation techniques, and in a coordinated manner.

4.2 System Model

The LSA is modelled between one demand MNO under the same assumptions described in Chapter 3, as well as an arbitrary incumbent. The LSA bands are available to be utilised over the entire coverage area of the demand MNO. On the other hand, the incumbent is assumed to follow a dynamic and random activity pattern. In LSA depending on the type of incumbent, temporal/spatial/spatial activity pattern may vary. The duty cycle of individual incumbent transmissions varies significantly for each service. Services with mobility result in a high degree of locality and temporal range from few meters up to tens of kilometres, on the ground or over the air. The positioning of some, might be maintained secrecy in general, and thus the NRA might act on behalf of the governmental entities. So, the incumbent in this thesis is considered arbitrary where no information is known apart from an interference threshold. The incumbent may randomly/occasionally appear in some part of the MNOs network without any notice resulting in geographical overlap with the demand MNO which may range from part of a single cell up to multiple cells, occasionally. Thus, the LSA bands are revoked by the incumbent dynamically. We assume the LTE-A MNO is capable of CA and may utilise the LSA bands aggregated with owned bands, or individually. Upon request by the incumbent, the LSA bands should be deactivated in identified area. Thus, there is no need to shut down the BS entirely, but to steer the traffic to its own band. Any service degradation (e.g., the data packet loss probability) incurred by the unexpected band revocation may be observed due to load of the cell. We also assume the location and power of incumbent are not known due to confidentiality, which forms the worst-case scenario of LSA scheme. This scenario can be justified as investigated in pilot trial in Italy [38], and [37][1]. It is aimed that through the REM-based approach, detection of the incumbent and identifying the potential interfering geographical area that how many cells (or/which part of cell) should be deactivated. This increases the chance of more geographical locations to keep serving their users in the LSA bands. In Figure 4.1, the cell specified in red, is assumed to be in the overlap area of randomly moving incumbent, where no information from it is known.

4.2.1 REM-based LSA Model

In [119] the authors investigate three different actions that each cell of the MNO has to perform when LSA incumbent appears in an area which overlaps with cellular system. An interference threshold -95dBm has been considered to identify which cells should take an action and which cells can transmit with no modification. The methods are; using offline and conservative propagation models, Down-tilt, and Power reduction. If

[1]Mainly the focus is on network related aspects of LSA such as reduced band evacuation to below 40 seconds compare to initial trial which was 60s.

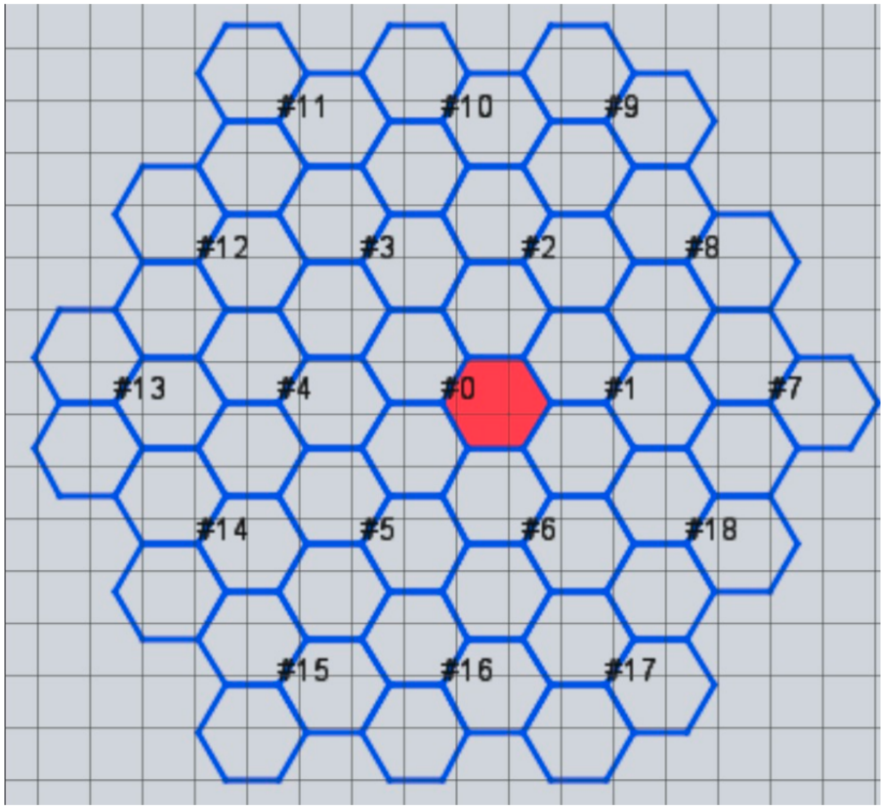


Figure 4.1: Constructed REM Environment

offline and conservative propagation models are applied it is shown that out of 57 cells only 16 cells in further distance can transmit and the rest must be shutdown. Shutdown is not ideal which reduces the opportunity of utilising the LSA band specially the total number of cells in the network and might not be necessary. The two other methods help to keep some cells still transmitting but the power level should be reduced or antenna tilt might need to be changed. The authors perform step by step reduction of BSs power in the network to identify at each step how many cells can keep transmitting. It is shown that by reducing the power from 46dBm to 19dBm which , higher number of cells (34) can transmit with no shutdown which is huge. Downtilt provided much lower success as with 15 degree (from its origin i.e., 6 degree) of downtilt only 12 cells can transmit and the rest should be shutdown.

Given above discussion, REM-enabled LSA is investigated in this Chapter. The algorithm is applied for REM construction the same as of Chapter 3 for REM-based IOSS. The REM construction procedure is summarised in Algorithm 2.

Algorithm 2: REM-Based LSA Construction Algorithm

2

Data: Set of sensors/data points K = {k_i} i=1,…,n
Data: Target point p at location (x_p , y_p)
Data: Power spectral density Z(k_i) of data point at location (x_{ki}, y_{ki}) on RB_r
Result: Estimated power spectral density Z_p in a location (x_p, y_p) for each RB_r
K ← Ø
for all RB_r do
  for all data points in the set k_i do
   Estimate Z(k_i)
    K ← K ∪ {Z(ki)}
    return K
  interpolate K
 Return Z_p
end
end

The entire cellular network is divided on square grid layout which is shown in **??**for better management of the measurements and SOP estimations. The placement of sensors are even across the square grids with equal distance, with n sensors per square grid. The sensors at their location (x_i, y_i) perform RSS measurement over the LSA-BW (In the form of RBs compatible to be used by LTE-A). The measurements are sent to the REM center for estimation of RSS unobserved area (x_p, y_p). The measurement data as a set K are interpolated and SOP map as an array over LSA-BW is generated.

The LTE-A network operates on the LSA bands, and via REM created above the network will be monitored to identify where/when the incumbent starts to transmit. Based on 2. When the LSA incumbent starts to transmit REM must recognise this to inform the LTE-A to evacuate the respective cell(s). REM can be notified the attendance of the incumbent in two ways. One would be through an interface between them with a reliable data rate and low latency. The other method would be that REM stores SOPs allocation in a database. So from the database, REM is aware that the BW is being utilised at a location is by the LTE-A. If the BW has not been allocated to the

LTE-A, but is being used, it can assume that the is being used by the incumbent.

4.3 Performance Evaluation

Back in our discussion of the SOTA above, and REM mechanism above we discuss the outcome of the simulation here. It is worth to note that here the objective is how to identify and decrease EZs to achieve higher gains (SOPs/capacity) from the LSA, subject to avoiding any interference to the incumbent, and, therefore the post processing reactive tasks of LTE-A for the band emption such as power adaptation, load balancing or traffic steering to the adjacent cells are not considered.

From the figure 4.2 it can be observed that the EZ is significantly reduced with respect to the SOTA, from 41 cells, to 3 cells[1] as a result of REM-based approach. The reason is that unlike offline propagation based approach, the interference fields are measured in a live (real-time) manner. As the real interfering areas are monitored (can be one cell or multiple cells) there is no need to shutdown all the BSs upon arrival of the incumbent. The power status of each cell through REM approach is depicted in Figure 4.2, which shows that the majority of cells can stay in operation mode (active) without the need to reduce power or perform shutdown.

[1]For the purpose of simulation the measurements the same as Chapter 3 are modelled by terrain 3GPP propagation modes. In real world real measurements are performed.

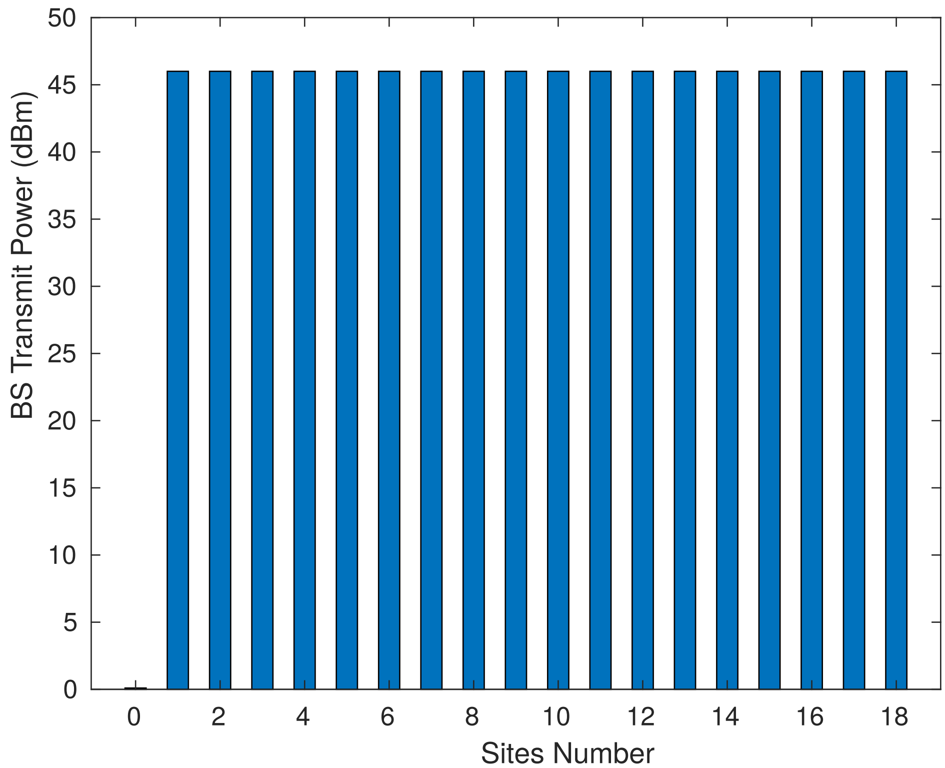


Figure 4.2: BSs Activity in the co-existence area

As a result of reduction in EZ, which means that the LTE-A can rely on the LSA-BW to serve its UEs, the total system throughput is significantly improved compared to the baseline LTE-A, by 80%, and the propagation based method in SOTA. The results are shown in Figure 4.3. It is worth to note that, this gain is subject to frequent attendance of the LSA incumbent. In the case that the incumbent does not transmit for long term, the gain from propagation-based approach also will be promising. However, in the case of frequent transmission, this approach fails to provide gain for the LTE-A.

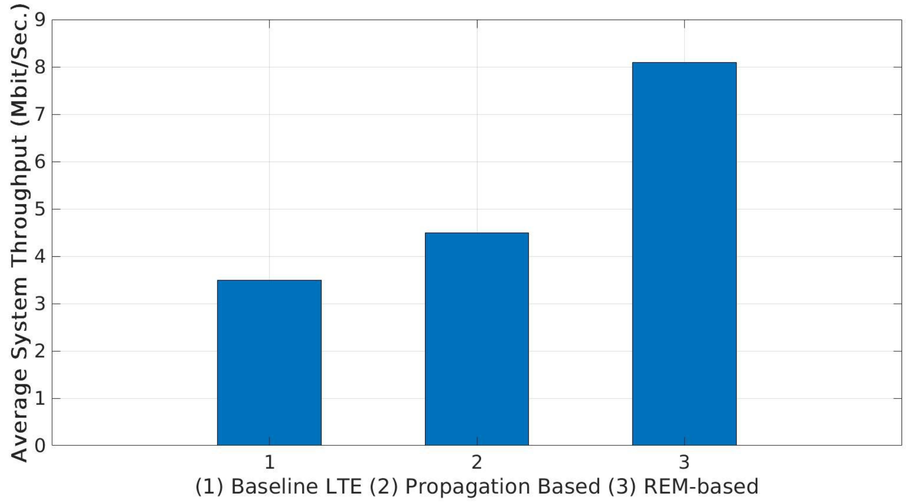


Figure 4.3: Average system throughput

This value has been achieved through the simulation. To investigate the cost of deployment the proposed approach can be assessed analytically, subject to some information from the incumbent (such as realistic threshold).

4.4 Summary and Discussion

Through REM-based LSA, the EZ is significantly reduced to the real-time detected overlapped area. Here, a worst case scenario of LSA incumbent as an arbitrary type with unknown information has been considered. However, the operational footprint for incumbents is application specific ranging from Amateur services services, Fixed Service systems, telemetry, PMSE, and, therefore, is mainly driven by the types of deployment described. Some of them are over the ground some are over the air. The duty cycle of individual incumbent transmissions varies significantly for each service, users with mobility result in a high degree of locality and temporal range from few meters up to tens of kilometres, on the ground or over the air. The positioning of some, might be maintained secrecy in general, and thus the NRA might act on behalf of the governmental entities. For some services, no single separation distance, guard band or signal strength limit can be provided to guarantee co-existence with LTE-A sometimes static exclusion zones cannot be applied. Co-existence can be achieved through coordination on a case-by-case basis. Besides, the performance of LSA depends on activity pattern of incumbent. Identification of realistic threshold is also very important to both satisfy LSA-incumbent and LTE-A users. In the case that multiple systems (such as MNOs) participate in spectrum sharing proper pricing policies must be define to allocate fare scale of LSA-BW to the system and avoid aggressive reuse of the BW [177].

Chapter 5

Epilogue

The SS is not a new concept and has been explored in research since last decade or so. At every stage new opportunities are introduced/authorised through the regulations, and various promising techniques, algorithms, and policies are proposed and investigated in research. This indeed reflects the necessity of deployment of SS to address the capacity related issues of almost all the spectrum grade service providers, namely mobile cellular systems, in the near future, as the long-term exclusive allocation of additional spectrum might no longer be feasible. However, the real-world deployment of this concept is subject to broader research on the concerning challenges, and uncertainties, and probable negative impacts must be resolved. The SOTA approaches, either consider the conservative policies for allocation of shared bands which results in limited achievable gains, or completely on an opportunistic basis which does not catch the probable interference leading to uncertainty. This calls for adoption of techniques with a more efficient level of awareness of SOPs in the network in both spatial and temporal domains. This can be achieved through REM, which facilitates a paradigm shift towards a sensing assisted centralised decision making SS. The main concept of REM depends on total RSS at any location of interest per unit of time which allows broad awareness of SOPs in the network and SS benefits from it with relaxed interference constraints.

In Chapter 2, a comprehensive survey of existing SS schemes was presented. More precisely, an in-depth study of all the relevant concepts including licensing/authorisation regimes, their specifications and requirements, deployment scenarios, techniques, and SOTA challenges were provided. As a result, the two types of SS, i.e., IOSS, and LSA were identified as the most challenging types and were chosen for further investigation in this thesis. The four promising techniques were identified for enhancements/investigation to be applied. These include: IO-ICIC, Coordinated Beamforming, spectrum sensing, and REM. The IO-ICIC is a very promising technique to minimise negative impact of interference as a result of SS, specifically in the cell-edges. Moreover, the coordinated beamforming allows for simultaneous utilisation of spectrum, which results in excellent SUE. However, both techniques are subject to agreement between the MNOs to share some UE data (such as CSI). These two techniques can be mainly applied in IOSS (when only the MNOs are involved). However, the REM is found as a potential technique for both IOSS and LSA schemes.

As the implementation of REM has not been addressed in IOSS and LSA, an introductory study of SOTA REM was conducted in Chapter 3. The two main methodologies were identified comprising sensing-assisted propagation-based, and sensing-assisted interpolation-based REM, which have been applied for the sharing scenarios such as TVWS sharing, coverage hole detection in the LTE specifications, etc. Moreover, a set of challenges and assumptions were identified as important factors to facilitate implementation of REM. These include but not limited to; localisation accuracies, sensing accuracies, sensing information density vs REM accuracy trade-off, dynamics of information vs acceptable REM information validity in LTE, interpolation techniques error, etc. In addition, it is found out that, in the SOTA performance evaluation, mainly the focus has been on the performance of REM (in terms of accuracy of information and probability of false alarm and miss-detection), and the impact of applying REM in the uses cases mentioned above has not been investigated. Having a broad overview of all possibilities of the REM deployment, the most reasonable method (considering the characteristics of the mobile cellular networks) for the SS was chosen.

Consequently, in Chapter 4, the IOSS problem was formulated, and the novel REM-Enabled IOSS mechanism was proposed, implemented, and analysed for the two distinctive topologies of the MNOs (on the LTE-A platform). It was shown that the proposed approach which exploits spatial and temporal SUT information across the large-scale mobile cellular networks outperforms the SOTA approaches namely centralised based IOSS and sensing based IOSS. In both deployment topologies, the REM-based approach achieves better gain in terms of system throughput with almost no negative impact on the performance of the supply MNOs' network. Most importantly SUE was improved significantly for a cell (67%) and for the entire system 23% through this approach.

Moreover, the results were compared to the LTE-A baseline when no SS is applied with 37.5% system throughput improvement. It is found out that, due to the nature of LTE-A air-interface with the time granularity at TTI level (resource scheduling and RB allocation varies every TTI), the performance of this approach is dominated by the fast-varying SOPs in the time domain, meaning that the observations must be updated in every TTI (i.e., 1ms). Given that, in the areas that there is no UE of supply MNO, the measured RSS values can be assumed invariant (as there is no data transmission). However, the areas that the high density of UEs are distributed, (even though static UEs, and fixed sensors are assumed, resulting in no spatial variation) the update rate needs to be conducted in 1ms time intervals. By adding mobility to the UEs, it makes the procedure more dynamic and challenging (location wise), as is likely that at any location in the cell, there will be a new transmission.

The second point is the that, the MNOs are required to determine the location of interest along with their request for shared spectrum. Thus, adopting high resolution localisation of the UEs improves the performance and accuracy of REM-based IOSS. The complexity and overhead of the proposed approach were calculated and shown negligible compared to the gain that was achieved.

It can be concluded that without this approach IOSS is unlikely to happen unless the SOPs are guaranteed to be available for long term. It is expected that this approach will be a potential mechanism that contributes to real-time allocation of the RBs to the MNOs, rather long-term assignment.

Lastly, one important and realistic fact is that the traffic across multiple MNOs could be correlated and interdependent (i.e., symmetric). Thus, long term and frequent request for shared spectrum may require for cell planning in the demand MNOs' network, as assuming the supply MNOs always have spectrum to share is not a valid assumption. Assuming symmetric traffic load between the MNOs, it can be concluded that the IOSS contributes to SUE rather than capacity improvement.

Given the discussion above, in Chapter 5, the REM-Enabled LSA was investigated applying the same approach, as comparing to the IOSS, wider bandwidth is available under the umbrella of the LSA scheme. Through REM-based LSA, the EZ is significantly reduced. More precisely, compare to the SOTA approach, where multiple cells of an MNO were considered as interfering cells, and had to act; such as power reduction or cell shutdown, here, only the overlapped areas (MNOs cell and incumbent) are the real interfering area. This results in allowing multiple cells keep utilising the LSA bands, with no risk of interference, which significantly improves the overall system throughput of LTE-A by 80%, and no need for power adaptation or shutdown.

In this thesis, a worst-case scenario of LSA incumbent as an arbitrary type with unknown information has been considered. However, the operational footprint for incumbents is application specific ranging from Armature services, Fixed Service systems, telemetry, PMSE, and, therefore, is mainly driven by the types of deployment.

5.1 Further Work

In this section, potential future research directions and approaches are identified as an extension of this thesis.

5.1.1 Impact of adding Mobility to the network

Mobility as an inevitable part of mobile cellular networks, should be addressed in the investigation of both IOSS and LSA approaches, as it adds higher level of dynamics to the network in terms of localisation, which makes the control over sharing procedure more challenging. A detailed analysis of a REM-Enabled SS is required considering complexity of SOP awareness in the mobile cellular networks with dynamically varying location of the UEs. This problem can be investigated from information theoretic perspective and modelled with Shannon entropy to identify optimal SOP awareness.

5.1.2 Uplink of Mobile Cellular System

The downlink of MNOs were investigated in this thesis. To have a generic view of impact of REM in mobile cellular networks, the Uplink mode should be investigated to see how uncertainty of UEs (as oppose to the downlink where the power and location of the BS is fixed, the location and power of the UE as an interferer vary) affect the performance of REM. In this case it might be worthwhile to consider the UEs as an REM entity to perform measurements/sensing. However, this is subject to the signalling, and energy consumption budget of the MNOs. Moreover, the accurate localisation techniques should be applied to estimate the location of UEs with higher resolution compare to the available GPS [178] based techniques.

5.1.3 Practical Implementation Adapt to 5G Architecture and air Interface

The LTE-A specifications as platform was chosen in this thesis to investigate feasibility of REM in SS, due its stability, standardised system architecture, and air-interface resulting in maximum confidence over stability of the system and results. Having a successful investigation and promising results from the LTE-A platform, it is worthwhile to evaluate the performance of the REM based SS schemes over the 5G networks.

Given that through the new system architecture, some level of context information can be provided from the 5G architecture to minimise the burden of collection of context information (possibly location of UEs, etc.).

5.1.4 Extend To Licensed Assisted Sharing Scheme

The REM is a potential approach for the LAA sharing, which is sharing of Wi-Fi bands with the mobile cellular networks. So far, mainly fairness based approaches have been proposed and investigated in the literature for this sharing scheme. Comparing to the IOSS and the LSA, LAA has less sensitivity to interference constraints and QoS requirements (compared to the licensed sharing schemes) resulting in less challenges in the deployment of REM. As we discussed LSA incumbents are very conservative and define wide EZs. Besides from some of them almost no information is known. Whereas for wi-fi information such as location and usage patterns can be easily captured.

5.2 Spectrum Sharing in 5G

Diverse 5G use cases have been envisioned, spanning from enhanced-MBB to MTC. 3GPP defines frequency bands for the 5G New Radio interface according for both eMBB and IoT applications, including the ranges of 3–5 GHz and 24–40 GHz, respectively, as well as the existing LTE bands to support massive capacity demand. The 24–40 GHz bands suffer from a high penetration loss and propagation attenuation make sub-6GHz bands still critical for 5G. Spectrum regulations are being rethought and improved as the LSA, LTE-U, LAA sharing schemes have been introduced which together with current LTE can provide universal high-rate coverage and a seamless user experience. Although lower bands fail to support high data rates because of their limited bandwidth, applying CA can help improve this issue [179], [180].

In this context REM based approach can be a potential method to be applied to facilitate LAA and LSA efficiently. The main difference will be the characteristics of

5 new radio, and any modifications to the deployments of the MNOs in terms of RAN and network in general. As new features such as virtualization and an intelligent CN, may facilitate deployment and management of data in REM. Besides, this approach can be highly applicable to the case, the NRAs no longer allocate spectrum on a exclusive basis, and REM as an unbiased entity in the network can manage the dynamic spectrum allocation to the systems.

Appendix A

Simulation Set Up for Baseline LTE

The simulator in this thesis has applied the following parameters [36]. Moreover, the vienna system level simulator, version 1.9, has been applied[165], to generate the network, and used as an input for the simulator developed in this thesis.

Parameters

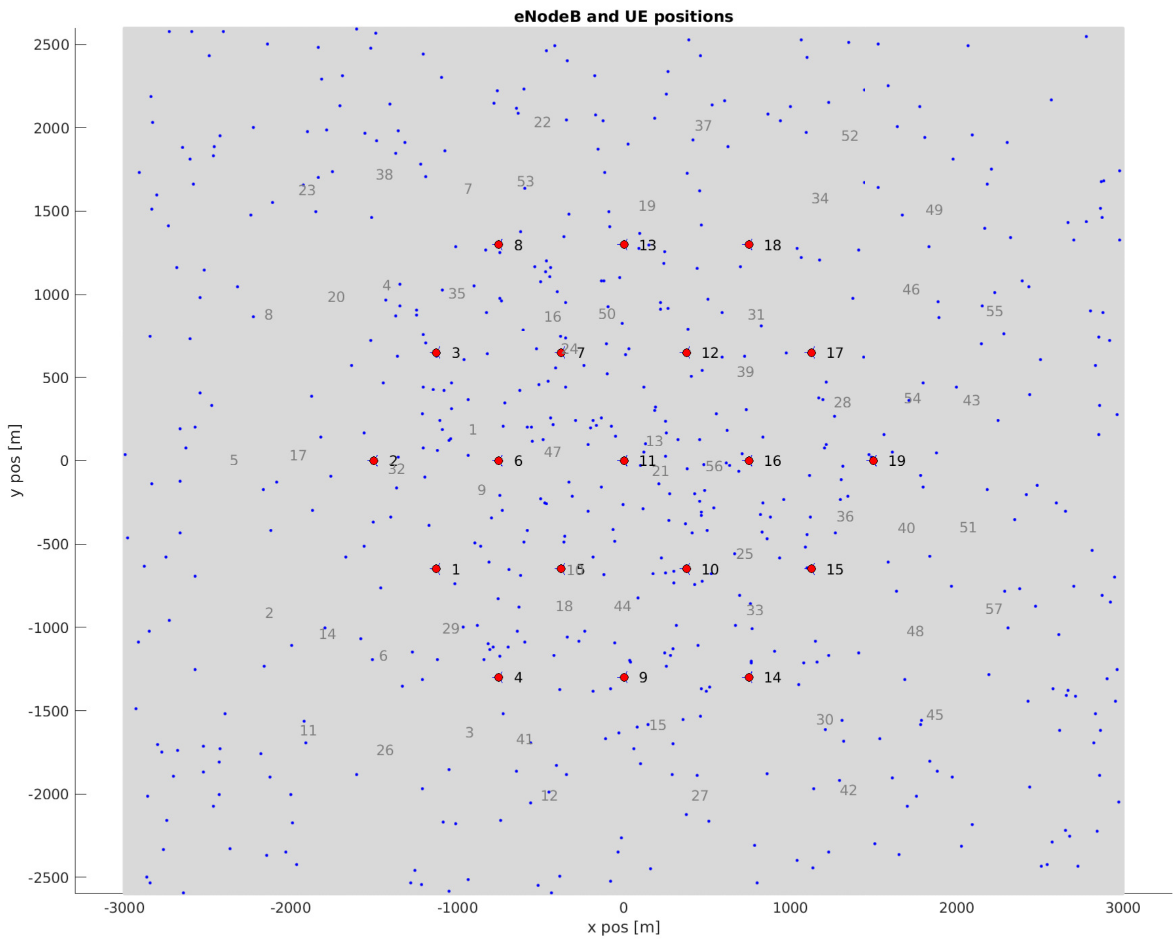
Figure A.1: LTE Simulation Parameters

LTE/DL/SISO Duplex mod: FDD	Parameter	Value
UE	Rx Antennas	1
	Antenna Height	1.5m
	Noise figure Noise floor	9 dB 2 dB
	Receiver thermal noise density	-174 dBm/Hz
	Antenna gain	0dBi (Omni directional)
	Speed	0 km/h (no mobility)
	Tx power	23dBm (ignored in the downlink)
BS	Transmission power per RB	29dBm (0.48 W)
	Antenna height	15m (above roof top)
	Max sector Tx power per Antenna	46dBm(fixed in the DL)
	Sector Antenna Gain	17 dBi (after cable loss = 15dBi)
	Noise figure	7 dB (ignored in the downlink)
	Tx antenna	1
Propagation and Channel Model	Macro scale fading: TR 36.942 (valid for height 0m to 50m), In urban environment Total Macro Loss = [PL: 128.1+37.6log10(d)] + [log F] (NOLS) • log F: log-normal shadowing (mean 0dB, and Std. 10dB) • d: distance between BS and UE (km) • fc carrier frequency (Vienna Simulator)	
	Micro scale fading: Rayleigh fading* *instantaneous SINR values per half RB, are gamma distributed random variables with mean value of wideband SINR as a result of Macro scale fading	
LTE radio frame structure	Total BW	20MHZ (10MHz-DL,10MHz-UP)
	Number of DL sub-channels (RB)	50
	Operating frequency	2GHz (variable)
	Sub-carrier spacing	15kHZ
	Sub-carrier (RB) BW	180kHz
	Useful channel BW	180KHz*50 =9 MHz
	Sub-frame; TTI	1 ms
	Frame duration	10 ms
	Reference signal transmission	CFI=2: 184REs [REs carrying control information per frame] (8 symbols per sub-frame carry reference signals)
	RLC mode	Unacknowledged mode (UM)* * HARQ delay (Round Trip delay), ACK, NACK, and retransmissions are not considered for UDP transmission
	Number of symbols per RB	7 OFDM symbol (normal Cyclic Prefix*) with symbol duration 14.28µsec, 168REs (Depends on the speed and corresponding delay spread, for rural areas, and high speed, max delay spread 15 µsec, the extended CP is considered => 6 OFDM

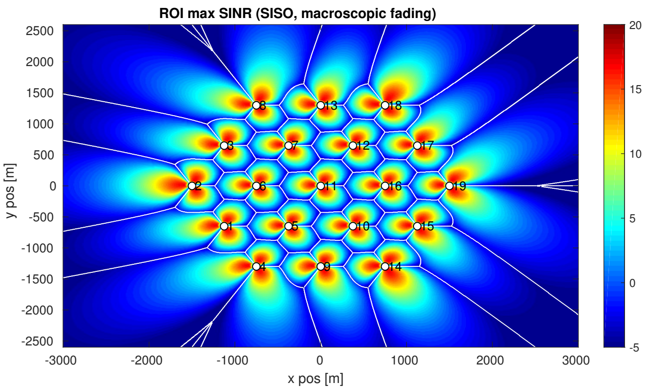
		symbols, with duration 17 μsec). This symbol duration is enough to avoid ICI due to delay spread and multipath propagation.
System/Network layout	Cell radius	250m
	Inter-site distance	750m (3R)
	Number of cells	57 cells [two rings/tiers]
	UE distribution Number of UEs per cell	Uniform distribution 100%outdoor Poisson random variable [min=5, max=10]
	Minimum distance	35m
	Maximum distance	400m (ignored for downlink)
	Number of BSs	Hexagonal grid, 19 cell sites, with sites in the corner of the cell, 65-degree sectored beam. Regular distribution [TR 136 942 V14.0.0]
Traffic type	BigBuckBunny real-time Streaming Video sequences 1920 × 1088 -pixel resolution Frame rate: 24 frame per second Codec: H.264 Delay Budget: 80ms [TR 23.107]	
General Informatio n	Simulation time: 67000ms (200TTIs are excluded as warm-up period)	
	Frequency re-use: 1	
	Cable loss: 0dB	
	User cell association: strongest RSRP	
	Minimum coupling loss=70dB	
	Interference Margin: 1dB (ignored for the downlink)	
	Control channel overhead, and reference signals are not modelled	
	Protocol headers in bytes: ROHC compression:3 (RTF/UDP/IP protocols), PDCP: 2, MAC:2 , CRC:3	
Link Adaptation: Modulation and coding schemes BLER 10%	QPSK ½ 16-QAM ½ 64QAM ¾	
Effective SINR calculation method for Transport Block Size Mapping	Exponential Effective SINR Mapping (EESM)	
CQI feedback report delay	5ms (assumed fixed for simplicity)	
Resource Scheduler	Round Robin	

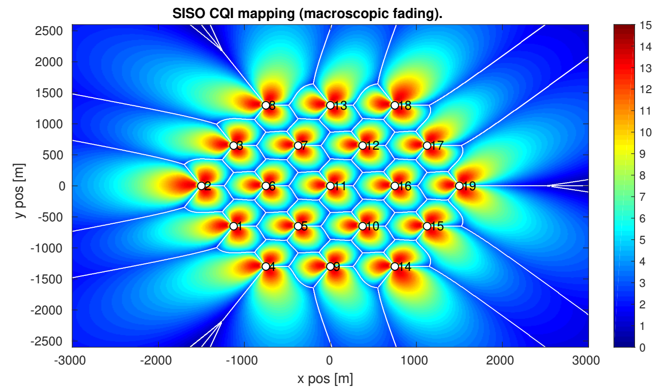
Environment

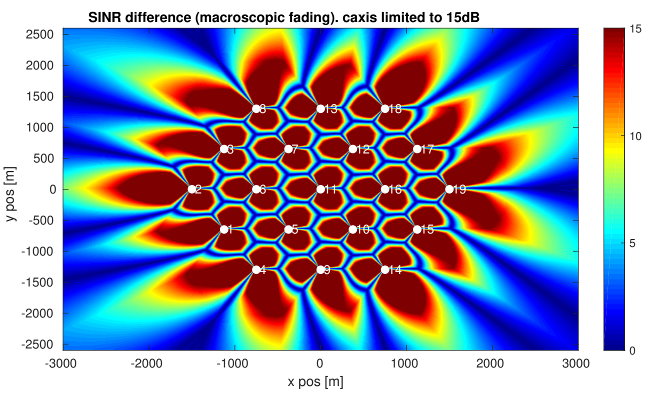
The following Figures show positions of the UEs (specified in blue dots) with respect to the BSs (specified with red dots). The UEs attached to the selected BSs are shown in black.

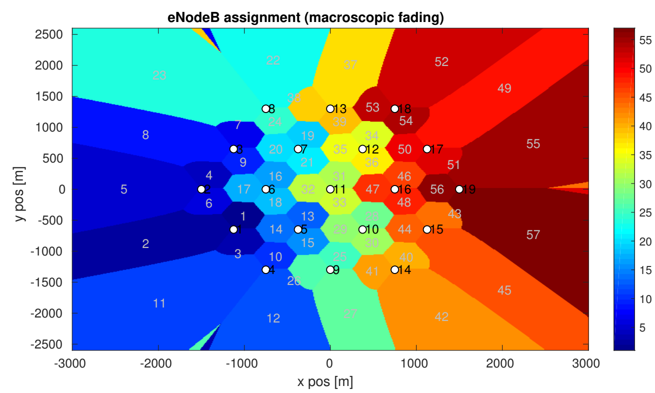


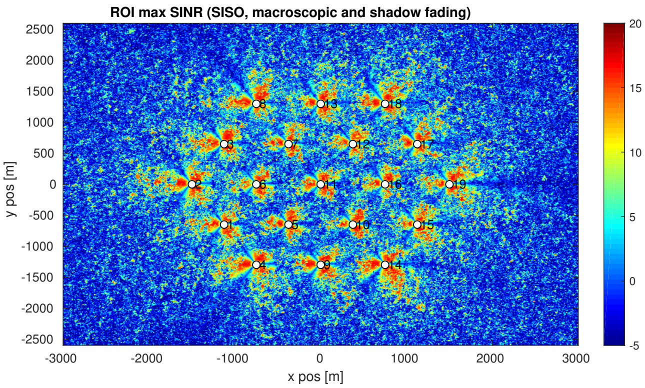
The wideband SINR, calculated with distance dependent macroscale pathloss and additional lognormal-distributed space-correlated shadow fading. The following figures show the impact of macro scale fading and pathloss on signal power.

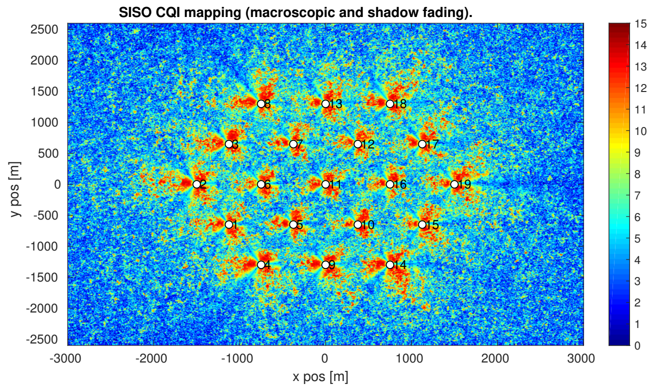


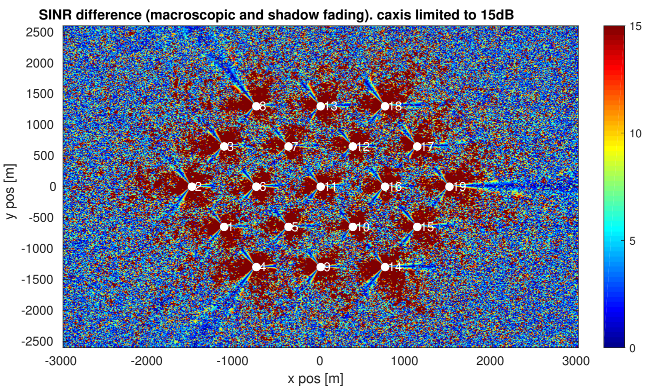


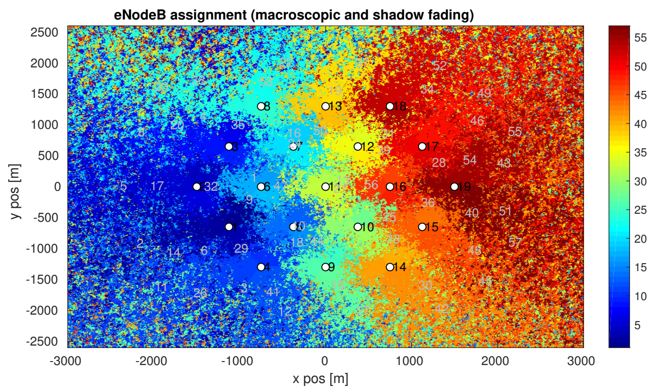




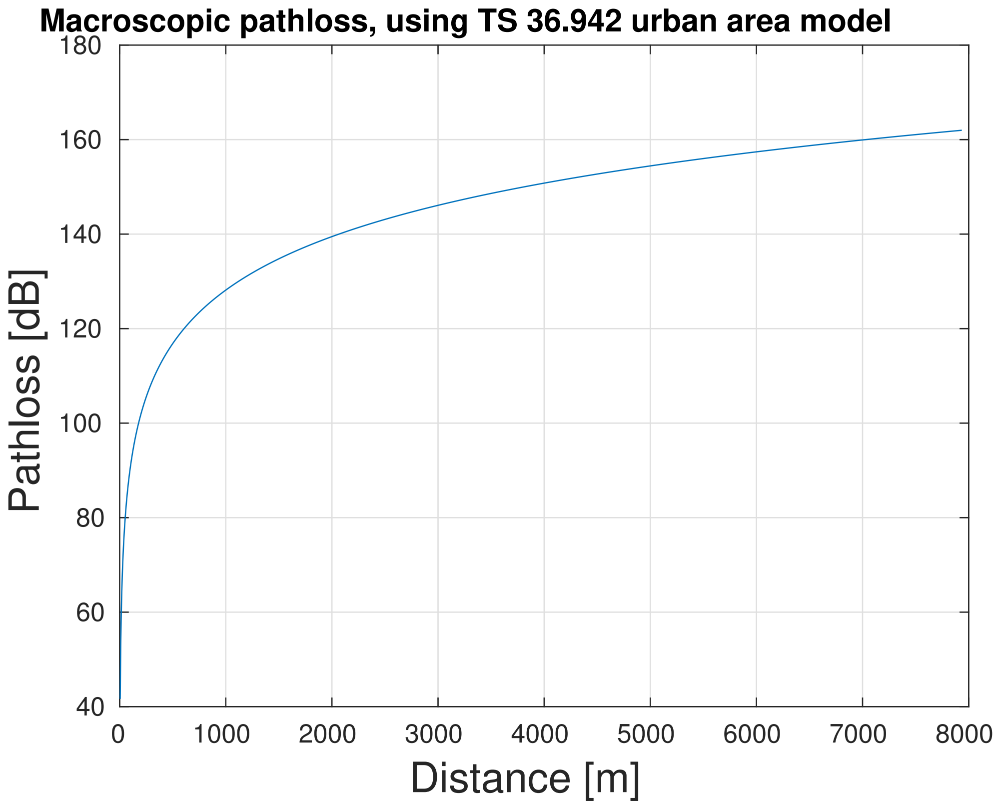

ROI max SINR (SISO, macroscopic and shadow fading)
y pos [m]
x pos [m]


SISO CQI mapping (macroscopic and shadow fading).
y pos [m]
x pos [m]


SINR difference (macroscopic and shadow fading). caxis limited to 15dB
y pos [m]
x pos [m]

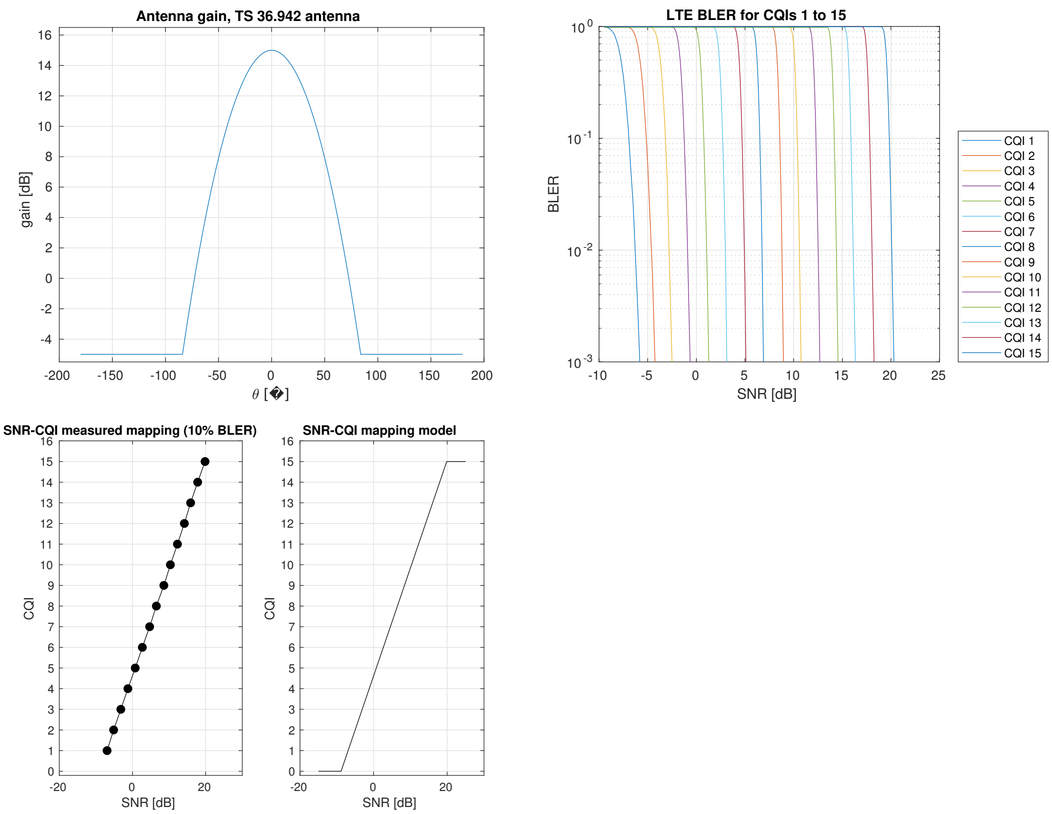

eNodeB assignment (macroscopic and shadow fading)
y pos [m]
x pos [m]

The pathloss is shown in the following figure; signal attenuation as a function of distance.



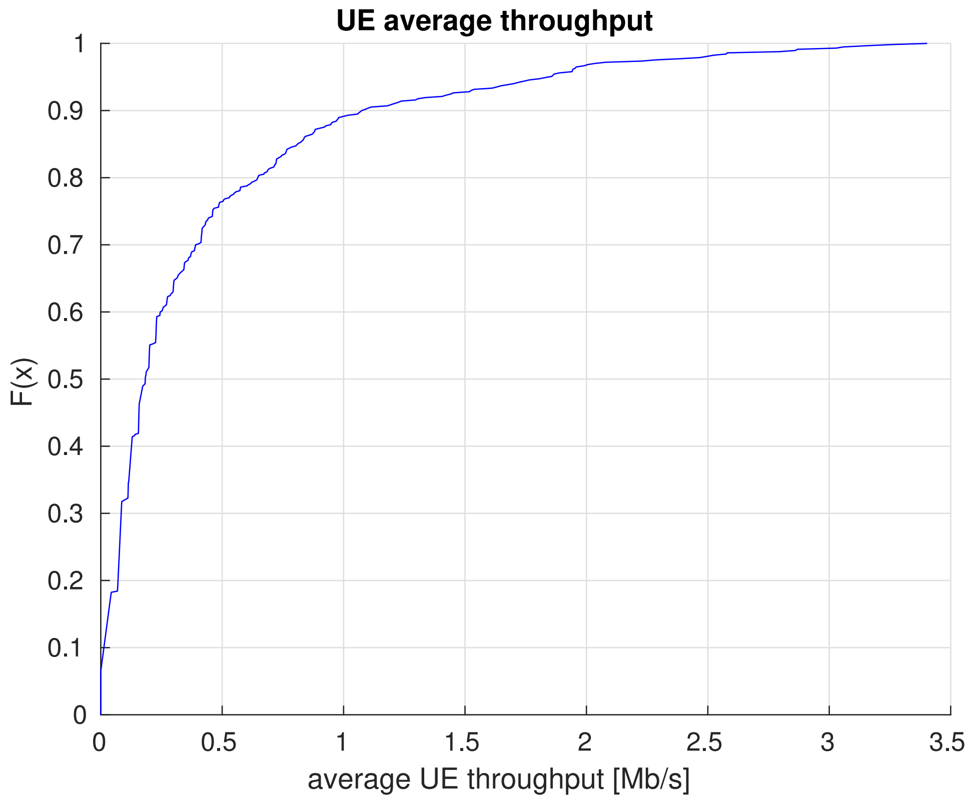
CQI mapping for resource allocation

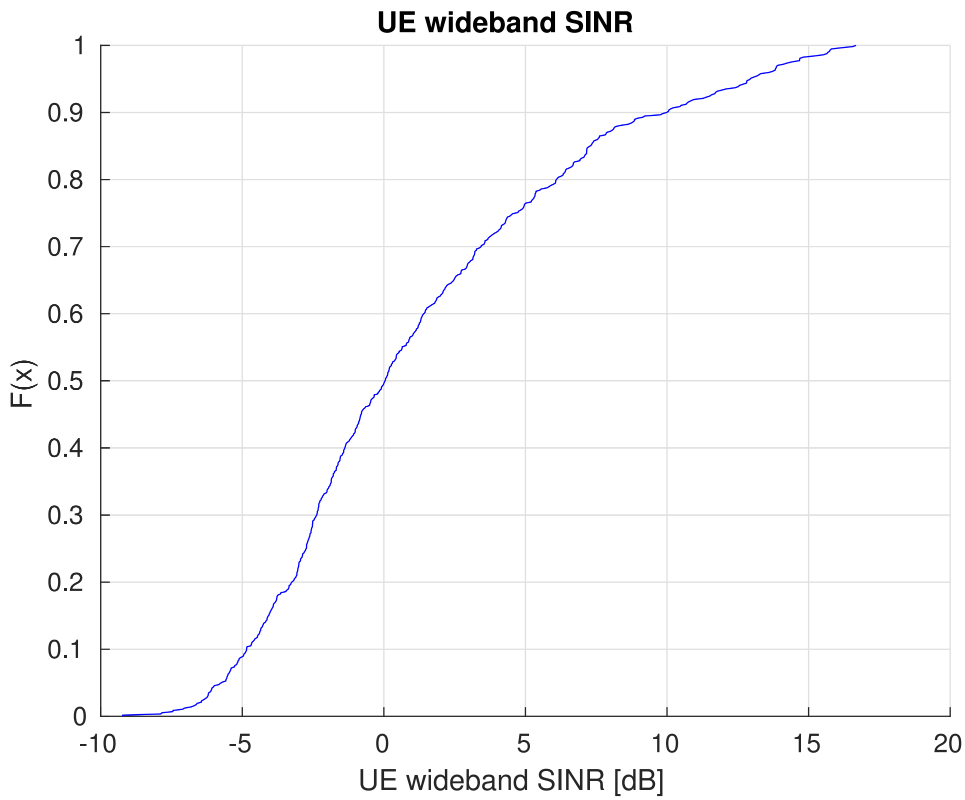
CQI BLER curves, and CQI mapping obtained from the 10 % BLER points, used for the purpose of resource allocation in the system.

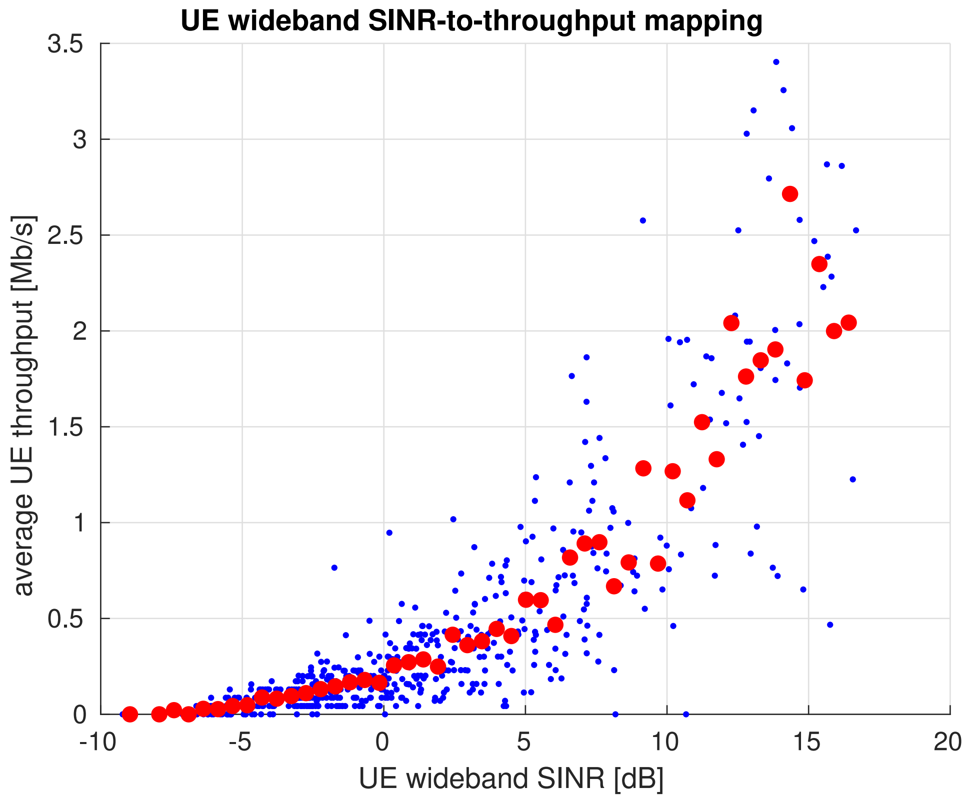


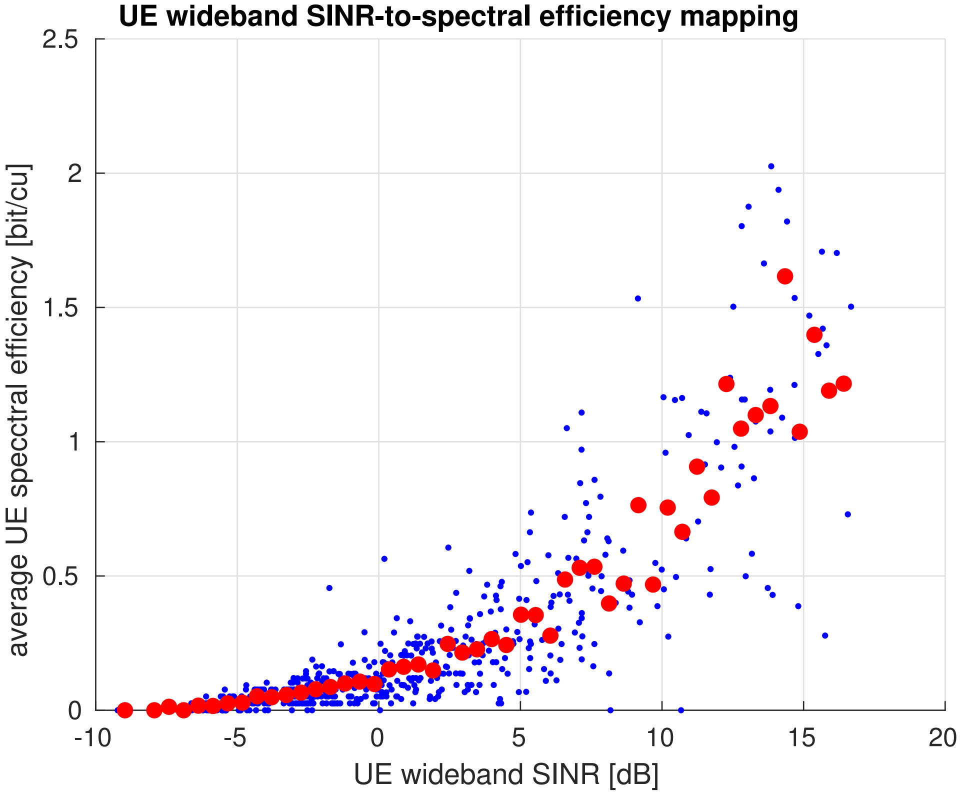
Baseline LTE Performance Benchmark

These curves are from link level simulator to identify for any SINR value what is the maximum achievable rate. The following graphs are generated by Vienna simulator for the purpose of validation (although values can be slightly different because at every run values randomly vary).


UE average throughput
F(x)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
0.5
1
1.5
2
2.5
3
3.5
average UE throughput [Mb/s]


UE wideband SINR
F(x)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-10
-5
0
5
10
15
20
UE wideband SINR [dB]


UE wideband SINR-to-throughput mapping
average UE throughput [Mb/s]
UE wideband SINR [dB]
0
0.5
1
1.5
2
2.5
3
3.5
-10
-5
0
5
10
15
20


UE wideband SINR-to-spectral efficiency mapping
average UE specctral efficiency [bit/cu]
UE wideband SINR [dB]
2.5
2
1.5
1
0.5
0
-10
-5
0
5
10
15
20

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