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

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***Abstract*—The ongoing development of mobile communication networks to support a wide range of superfast broadband services has led to massive capacity demand. This problem is expected to be a significant concern during the deployment of the 5G wireless networks. The demand for additional spectrum to accommodate mobile services supporting higher data rates and having lower latency requirements, as well as the need to provide ubiquitous connectivity with the advent of the Internet of Things sector, is likely to considerably exceed the supply, based on the current policy of exclusive spectrum allocation to mobile cellular systems. Hence, the imminent spectrum shortage has introduced a new impetus to identify practical solutions to make the most efficient use of scarce licensed bands in a shared manner. Recently, the concept of dynamic spectrum sharing has received considerable attention from regulatory bodies and governments globally, as it could potentially open new opportunities for mobile operators to exploit spectrum bands whenever they are underutilized by their owners, subject to service level agreements. Although various sharing paradigms have been proposed and discussed, the impact and performance gains of different schemes can be scenario-specific, and may vary depending on the nature of the sharing players, the level of sharing and spectrum access scheme. In this survey, we study the main concepts of dynamic spectrum sharing, different sharing scenarios, as well as the major challenges associated with sharing of licensed bands. Finally, we conclude this survey with open research challenges and suggest some future research directions.**

***Index Terms*—Licensed spectrum sharing, radio access technology (RAT), 5G, co-primary spectrum sharing (CoPSS), licensed shared access (LSA).**

I. Introduction

THE MASSIVE growth in mobile data traffic has become a significant concern for the development of future wireless networks. It is estimated that the required capacity demand, in order to accommodate such amounts of traffic load, will be remarkably increased by the growing use of mobile devices, such as smartphones to access diverse sets of broadband services and applications, as well as the development of new features like Machine Type of Communications (MTC) [1]–[3]. It is estimated that wide contiguous bandwidth from hundreds of MHz up to a few GHz will be required for the deployment of 5G systems [4], [5]. On the other hand, spectrum 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. [6]. Although cellular systems are expected to be capable of operating on sub-6GHz bands [1], these bands have already fragmented and assigned to the aforementioned spectrum users in an exclusive manner by the regulators [7], [8].

Mobile networks support a wide range of carrier-grade services with varying performance requirements. Some applications require contiguous bandwidth, whilst for others a wider bandwidth preferably in bands with desirable propagation characteristics and broader coverage (e.g., the bands below 1GHz) is required. For instance, the applications such as high-resolution video monitoring/streaming, large cloud-based file transfers, wireless sensors in the IoT sector, with high data rates, require wide bandwidth for data transmission [1]. In this respect, LTE-Advanced (LTE-A) specifications support operation with bandwidths of up to 100MHz, taking advantage of multi-carrier functionalities such as Carrier Aggregation (CA) [9], [10], and also other techniques such as Multiple-Input-Multiple-Output (MIMO) and relaying [11]. However, it should be noted that, there are some limitations in applying inter-band CA [12] (in which, component carriers are non-contiguous and belong to the different operating frequency bands) as it might require more Adjacent Channel Leakage power Ratio (ACLR) efficiency in the Physical Layer (PHY) [13]. Hence, the provision of wider bandwidth based on the aggregation of fragmented spectrum chunks, will result in new challenges.

Apart from the problem of CA in the fragmented bands, this also should be considered that the performance of MIMO techniques varies as a function of the Signal to Interference-plus-Noise Ratio (SINR) of receiver [14], meaning that the users with low SINR (typically less than 9-10dBm) cannot benefit from this technique to achieve higher data rates. Therefore, it would be unlikely for an end user to achieve the expected target peak data rate of 10Gb/s (of 5G systems [4]) by relying on the CA and multi-user MIMO techniques

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alone. In this regard, other solutions such as the deployment of millimetre Wave (mmWave) antennas are under intensive investigations in order to facilitate utilisation of the higher frequency bands (e.g., 17-to-30, 60, and 90GHz) in cellular communication networks, which have the potential to provide significant capacity improvements for both the Radio Access Network (RAN), as well as the backhaul [15]. More information of mmWave related studies can be found in [16] and [17]. In addition, the densification of small cells with low transmission power levels has been considered as a reasonable solution to improve frequency re-use. However, co-existence of small cells and macro cells in the same frequency bands introduces new types of interference [18], [19]. In contrast, dedicated allocation of licensed bands to the small cells will lead to spectrum underutilisation and is not of interest to the mobile operators [20]. Besides, the deployment of small cells is subject to additional costs in terms of, e.g., high-speed backhaul and additional infrastructure requirements [20].

A few possibilities have been recently investigated to provide additional *licensed spectrum* for mobile cellular systems. For instance, *spectrum refarming* has been broadly explored. The term spectrum refarming refers to the migration of non-mobile communication systems of their licensed spectrum, to the alternative frequency band(s) [21]. It follows the purpose of releasing the currently occupied bands with suitable propagation characteristics, which are appropriate for mobile systems uses. 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. Hence, refarming may not always be a feasible solution, as it will be a long term procedure and generates additional costs [22], [23].

Given above, the utilisation of licensed spectrum in a shared manner is a promising solution. The benefit of spectrum sharing is twofold; firstly, it allows improvement of the spectrum utilisation, and secondly, it can provide additional capacity for the users who require more spectrum for different types of services. A wide range of spectrum sharing schemes can facilitate utilisation of the different frequency bands (comprising licensed and unlicensed) belonging to various carrier grade service providers. The deployment of spectrum sharing is subject to meeting a set of pre-defined regulations and requirements, and can also involve various coordination protocols/techniques.

A number of international standardisation bodies currently focus on various aspects of spectrum sharing and its management. For instance, European Telecommunications Standards Institute (ETSI) focuses on *spectrum* sharing [24], and plans to apply cognitive techniques such as Radio Environment Maps (REMs) [25] (which is discussed later in this article), but the *infrastructure* sharing issues are not currently addressed [24] (the different types of sharing will be discussed in detail in the following sections). A recent study from the Third Generation Partnership Project (3GPP) specifications indicate increasing interest in various resource sharing scenarios, and how mobile operators can share common LTE radio resources, according to identified RAN sharing scenarios, whether as a shared deployment or as a leased asset [26], [27]. 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 [28].

On the regulatory front, bodies such as Office of Communications (Ofcom), and Federal Communications Commission (FCC) focus on solutions that can open up of new bands when spectrum sharing is performed among federal spectrum users, such as public sector, defence, etc., and mobile operators. 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 QoS, and therefore a "tragedy of the commons" [1] may ensue. The findings/recommendations have implications for the future viability of Wi-Fi in both public networks and potentially for outdoor *MTC* applications. The latest release of Ofcom consultations [1] indicate that, sharing as one possible supplement can address this problem. In addition, spectrum sharing has been broadly considered by *EU projects* such as METIS [29]–[31] and SAPHAYRE [32], which parts of their work are discussed briefly in this article.

The rest of the paper is organised as follows: The list of abbreviations applied in this article as well as their corresponding definitions, is presented in TABLE I. The discussion of published survey papers relevant to the context of spectrum sharing are provided in Section II. A taxonomy and definition of various terms used in the context of authorisation regimes and spectrum access schemes, between various types of sharing parties are provided in Section III. In Section IV, the implication of authorisation regimes (which explained in Section III) in mobile cellular systems, currently available licensed sharing scenarios and their corresponding use cases are defined. Besides, the currently available coordination techniques are explained. This is followed by Sections V and VI, where extensive survey of existing approaches for each of individual sharing scenario is provided in detail. We highlight several shortcomings and further required enhancements of spectrum sharing in Section VII, and finally we conclude the survey in Section VIII.

II. Related Work

A. Review of the State-of-the-Art (SOTA) Survey Articles

The context of spectrum sharing, under the umbrella of various terms, has been broadly studied in the literature for a decade or so. For instance, in Cognitive Radio Networks (CRNs), many surveys under Opportunistic Spectrum Access (OSA) and Dynamic Spectrum Access (DSA) terms have been carried out. These surveys mainly focus on the principals of CRNs and investigate the applicability of a wide range of available coordination protocols/methods, as well as the spectrum access/allocation/assignment techniques under various licensing regimes covering different spectrum ranges.

TABLE I
LIST OF ACRONYMS AND CORRESPONDING DEFINITIONS

Acronym	Definition
ACLR	Adjacent Channel Leakage power Ratio
ASA	Authorised Shared Access
BSs	Base Stations
CA	Carrier Aggregation
CAPEX	Capital Expenditures
CDMA	Code Division Multiple Access
CEPT	Conference of European Postal & Telecommunications
CN	Core Network
CoMP	Coordinated Multi-Point
CoPSS	Co-Primary Spectrum Sharing
CQI	Channel Quality Indicator
CRNs	Cognitive Radio Networks
CSI	Channel State Information
CUS	Collective Use of Spectrum
DECT	Digital European Cordless Telecommunications
DSA	Dynamic Spectrum Access
DVB	Digital Video Broadcast
ECC	Electronic Communications Committee
ETSI	European Telecommunications Standards Institute
EZs	Exclusion Zones
FCC	Federal Communications Commission
FDD	Frequency Division Duplex
FSA	Fixed Spectrum Allocation
GAA	General Authorised Access
GT	Game Theory
ICIC	Inter Cell Interference Coordination
IMT	International Mobile Telecommunication
IoT	Internet of Things
ISM	Industrial, Scientific and Medical
ITU-R	International Telecommunication Union-Radiocommunications
LAA	License Assisted Access
LSA	Licensed Shared Access
LTE	Long Term Evolution
LTE-A	LTE-Advanced
LTE-U	LTE-Unlicensed
MAC	Medium Access Control
MBB	Mobile BroadBand
MIMO	Multiple-Input-Multiple-Output
MME	Mobility Management Entity
mmWave	millimetre Wave
MNOs	Mobile Network Operators

Acronym	Definition
MOCN	Multı Operator Core Network
MORAN	Multi Operator Radio Access Network
MTC	Machine Type of Communication
MVNO	Mobile Virtual Network Operator
NB	Nash Bargaining
NE	Nash Equilibrium
NRA	National Regulatory Authority
OAM	Operation Administration and Management
Ofcom	Office of Communications
OFDM	Orthogonal Frequency Division Multiplexing
OPEX	Operational Expenditure
OSA	Opportunistic Spectrum Access
PAL	Priority Access License
PCH	Pilot Channel
PDCCH	Physical Downlink Control Channel
PHY	Physical Layer
PMSE	Program Making and Special Events
PRB	Physical Resource Block
PUs	Primary Users
QoS	Quality of Service
RAN	Radio Access Network
RATs	Radio Access Technologies
REMs	Radio Environment Maps
RNC	Radio Network Controller
RRM	Radio Resource Management
SAS	Spectrum Access System
SG	Serving Gateway
SINR	Signal to Interference-plus-Noise Ratio
SLAs	Service-Level Agreements
SOI	Spectrum Opportunity Index
SON	Self-Organising Network
SOTA	State-Of-The-Art
SUs	Secondary Users
TDD	Time Division Duplex
TD-LTE	Time-Division LTE
TTI	Transmission Time Interval
TVWSs	TV White Spaces
UE	User Equipment
UMTS	Universal Mobile Telecommunications System
WSNs	Wireless Sensor Networks
3GPP	Third Generation Partnership Project

In [33], the authors classify spectrum management algorithms under centralised "dynamic spectrum allocation" and distributed "dynamic spectrum selection" terms. The former covers spectrum sharing scenarios between different RATs, and it is managed by a centralised management entity for both licensed and unlicensed spectrum. The latter however, involves all OSA sharing types in CRNs incorporating distributed techniques (sensing technique in this work is mainly considered). Some technical challenges such as, traffic prediction, signalling overhead, and complexity are discussed, and based on these challenges a general comparison between the two approaches is provided.

In [34], the authors analyse the challenges facing OSA schemes, including required interactions among multiple users for dynamic spectrum opportunity detection, "trade-off between sequential sensing information", "cost" and "convergence speed", as well as the "trade-off between exploitation and exploration in the absence of prior statistical information". In this context, a comprehensive review and comparison of different decision-theoretic solutions, such as, "game models", "Markovian decision process", "optimal stopping", "multi-armed bandit", and their strengths and limitations are provided.

In [35] and [36], the authors provide comprehensive survey on the challenges related to the spectrum decision/assignment in CRNs including; "spectrum characterisation process", "primary-system activity modelling", "spectrum selection", and "reconfiguration".

In [37], the authors investigate techniques including; spectrum sensing, geo-location database, beacon, and database-assisted spectrum sensing which are used for spectrum opportunity detection, highlighting the main aspects of their implementation. A comprehensive qualitative assessment of the viability of each of these techniques for spectrum sharing in three different RATs; radar, TV White Spaces (TVWSs), and cellular systems, is provided.

In [38], a survey on resource allocation challenges in CRNs according to different design techniques such as, "SINR-based", "transmission power-based", "centralised and distributed" methods of decision making, is presented. The authors provide mathematical formulation of each resource allocation problem. A study on the common CRN optimisation methods is presented in a tutorial manner. Besides, research challenges in spectrum allocation are discussed comprising distributed spectrum allocation techniques, for the design of efficient spectrum sharing techniques. Moreover, "mobility

TABLE II
SURVEY PAPERS IN THE FIELD OF SPECTRUM SHARING

Paper title	Research topics reviewed
"A Comparison Between the Centralized and Distributed Approaches for Spectrum Management" [33]	=> Classifies spectrum management "algorithms" under centralised Dynamic Spectrum Allocation and distributed Dynamic Spectrum Selection terms. => The basic functionalities of the aforementioned algorithms are discussed. => Enabling technologies and technical challenges of the algorithms are investigated. => A comparison between the two algorithms is presented.
"Decision-Theoretic Distributed Channel Selection for Opportunistic Spectrum Access: Strategies, Challenges and Solutions" [34]	=> Decision-theoretic solutions for channel selection and access strategies under OSA are presented. => A comprehensive review of the SOTA on decision-theoretic solutions to analyse strengths and limitations of each kind of existing decision-theoretic solutions are discussed. => The operational procedure of OSA is discussed. => Several future research problems for both technical content and methodology are presented.
"Spectrum Decision in Cognitive Radio Networks: A Survey" [35] "Spectrum Assignment in Cognitive Radio Networks: A Comprehensive Survey" [36]	=> An overview of CRNs is presented. => Spectrum assignment in CRNs is discussed. => Existing techniques for spectrum allocation in the literature are presented and corresponding challenges are studied.
"Radar, TV and Cellular Bands: Which Spectrum Access Techniques for Which Bands?" [37]	=> Discusses and qualitatively evaluates relevant spectrum sharing techniques including; spectrum sensing, cooperative spectrum sensing, geolocation databases, and the use of beacons for spectrum opportunity detection in the radar, TV, and cellular systems.
"Radio Resource Allocation Techniques for Efficient Spectrum Access in Cognitive Radio Networks" [38]	=> Focuses on resource allocation techniques in CRNs such as SINR-based, transmission power-based, centralised and distributed methods of decision making. => CRNs optimisation methods are overviewed, accompanied by a comprehensive study of the resource allocation problem formulations. => The challenges of spectrum assignment are discussed, focusing on dynamic spectrum allocation, and spectrum aggregation.
"Cognitive Radio for Smart Grids: Survey of Architectures, Spectrum Sensing Mechanisms, and Networking Protocols" [39]	=> A comprehensive survey on the CRN in smart grids, including the system architecture, communication network compositions, applications, and cognitive radio-based communication technologies is provided. => Potential applications of CRN-based smart grid systems are discussed. => A classification of cognitive-based spectrum sensing approaches is presented. => A survey on cognitive-based routing protocols, and interference mitigation schemes is provided.
"A survey of MAC issues for TV white space access" [40]	=> A comprehensive survey on MAC-related challenges for cognitive access to the TVWSs is provided. => Discusses potential approaches to overcoming the challenges, and investigates open research issues. => Reviews regulatory activities in several countries and worldwide standardisation efforts for TVWS access.
"Overview and comparison of recent spectrum sharing approaches in regulation and research, From opportunistic unlicensed access towards licensed shared access" [41]	=> An overview of the spectrum regulatory framework covering the different forums is presented. => It reviews the specific sharing related studies and models developed in the different regulatory forums, as well as dynamic sharing models developed in the research domain. => An analysis and comparison of the most "topical dynamic sharing" models are presented.

functions" for frequency handoff are studied, to enable CA in "secondary systems".

In [39], the authors investigate how cognitive techniques can be applied in smart grid applications. They present the strategies for integrating cognitive-based techniques into the smart grid networks. The authors also study the architectures of CRNs, as well as the cognitive-based spectrum sensing approaches, routing protocols, and interference mitigation schemes for smart grids. Other concepts, such as security, privacy, power, and energy related issues are also discussed.

In [40], a survey on Medium Access Control (MAC) related issues for the utilisation of TVWS in a shared manner is provided. The authors discuss potential techniques, including geo-location database and sensing, to addressing these issues and also investigate the relevant open research challenges. A survey on co-existence related issues is also presented.

In [41], the authors review a vast range of spectrum sharing schemes (including both unlicensed and licensed) under the umbrella of the "spectrum regulation and wireless communications research domains", and activities related to the development of spectrum sharing. This work provides study of the European and U.S. regulatory approaches for spectrum sharing, including Licensed Shared Access (LSA), Collective Use of Spectrum (CUS), and Spectrum Access System (SAS). A comparison of these approaches is also presented. Moreover, some factors for developing a successful sharing model are discussed, which comprise guaranteed protection rights of entrant users "without impact to the legacy systems", and a "reasonable opportunity for an entity that wishes to access a shared spectrum", considering the cost and complexity of the deployment.

The concepts covered in the discussed surveys are summarised in TABLE II.

B. Contribution of This Article

From the previous section, it can be observed that there are extensive literature surveys that focus on spectrum sharing and access techniques in CRNs. This article, however, provides a survey of the SOTA on *licensed spectrum sharing scenarios* in *licensed bands*, ranging from *inter Mobile Network Operators (MNOs) spectrum sharing* to *LSA*, where sharing players require spectrum access and QoS guarantees (the shaded blocks of the taxonomy in Fig. 1, represent the contribution and scope of this article). Therefore, we exclude the concept of DSA/OSA from the scope of this article. It has to be noted that, although first and foremost, the focus of this article is on the licensed spectrum sharing schemes, we review a broad range of spectrum sharing licensing/authorisation regimes in order to introduce relevant terminologies and facilitate better understanding of the contribution of this paper, and highlight the differences from existing works. The end goal of this article is to provide an insight into practically viable *licensed spectrum sharing schemes* that enable MNOs to access *sub-6GHz licensed bands* in an efficient shared manner. We emphasise that, this paper investigates the impact of spectrum sharing on *mobile cellular networks*, and therefore we explore the scenarios in which at least one sharing player is an MNO. To summarise, this article:

- Provides an in depth survey of existing licensing/authorisation regimes, their specifications and requirements.
- Identifies potential deployment scenarios in mobile cellular networks, which can benefit from spectrum sharing.
- Provides detailed survey of existing coordination protocols applied in the SOTA licensed sharing schemes (i.e., inter-operator spectrum sharing and LSA), their advantages and shortcomings.
- Investigates business and regulatory aspects of licensed spectrum sharing for the practical deployments.
- Provides an extensive survey on various types of the proposed inter-operator spectrum sharing in the literature, and their achieved gains to investigate their viability for the practical deployment.
- Provides an extensive survey on the SOTA LSA framework, which is now in its initial steps for deployment.
- Identifies several existing challenges in licensed spectrum sharing schemes, including both inter-operator spectrum sharing and LSA and recommends several research directions for further enhancements.

III. Taxonomy of Spectrum Access Methods and Authorisation Regimes

In this section, the classification of various available authorisation regimes (licensing policies), which determine the allowable levels of spectrum sharing 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: 1) degree of QoS guarantees, 2) level of spectrum access guarantees, 3) spectrum license fee, and 4) spectrum utilisation efficiency, targeting different spectrum ranges. In fact, service providers (mobile operators in the scope of this article) can apply one/combinations of the licensing policies depending on their level of QoS and interference sensitivity, budget and spectrum requirements.

Spectrum sharing in future cellular systems (namely 5G), has a scope far beyond that addressed in the previous studies of CRNs. In CRNs, *radios* are capable of learning/monitoring the environment and change their transmission parameters adaptively based on the observations [42]. In this way, the cognitive radios capture spectrum opportunities (also known as "spectrum holes") with the aid of wide range of detection techniques in a dynamic manner. This helps improve spectrum usage efficiency, and therefore mitigates the desired-spectrum scarcity problem. However, access to the bands is opportunistic and in an unlicensed manner, i.e., with unpredictable access and interference protection guarantees when multiple service providers co-exist [43]. 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), new licensed spectrum access methods have been offered by the regulatory bodies. In the following subsections, we discuss in detail all the currently available authorisation regimes, which are expected to be applied in 5G cellular systems.

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 Fig. 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 [29]:

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 [22]. 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 mobile operators) 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 to the license holders. 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 the adoption of robust coordination protocols among sharing players which is discussed in detail

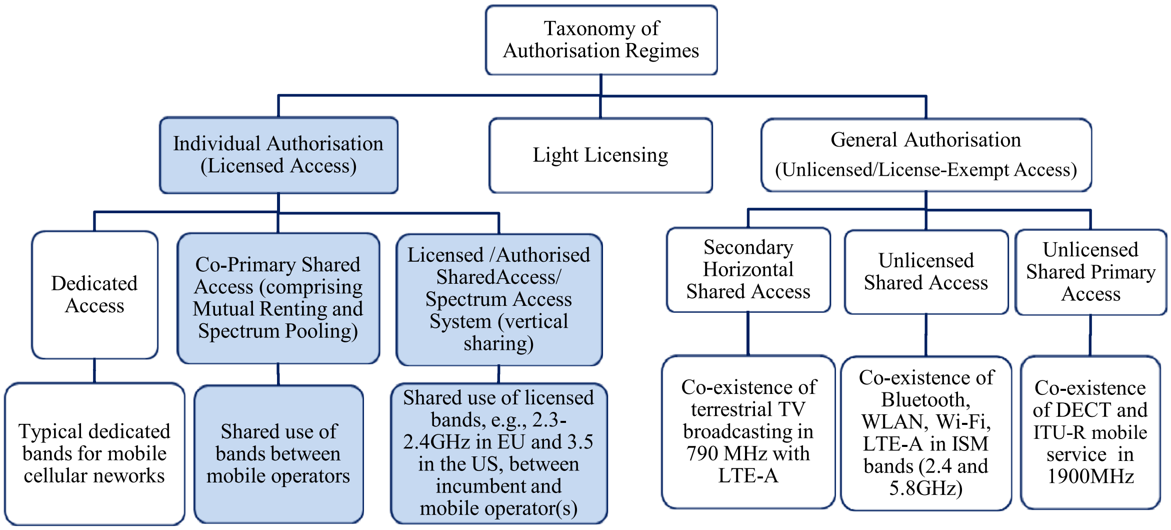

Fig. 1. Taxonomy of spectrum access methods and authorisation regimes [29], [44] (the shaded blocks represent the scope of this work).

later. The currently available licensed access methods to the licensed bands are:

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 regulation [45]. The two relevant access methods under the umbrella of co-primary shared access are [22].

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 prove insufficient to meet the capacity demand. This access scheme, as a complementary opportunity, seems to be beneficial for the MNOs 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 [29], [46].

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 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 [29], [47], or by the instantaneous spectrum opportunity detection, taking advantage of 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 [21], [22].

b) Licensed shared access (LSA): LSA is an extension of ASA concept, which is proposed by the Conference of European Postal & Telecommunications, Electronic Communications Committee (CEPT ECC) [48], 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 (known as incumbent) can share spectrum with one or more mobile communication systems 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 [49], [50].

Although in Europe, the current candidate channels are 2.3-2.4GHz (which can be used in LTE), future deployments of LSA are expected to go beyond the IMT bands and will not be limited to mobile cellular networks use only [51]. Although the terms LSA and ASA essentially refer to the same paradigm, in some works such as [49] and [52] the differences between them have been highlighted as follows: 1) the ASA concept is a specific case of LSA where the licensee is an MNO, 2) the requested level of authorisation, which in ASA remains open without any specific clarifications, 3) the target bands in ASA are only suitable to be used for cellular systems, whereas in LSA, it is intended to cover as many bands as possible and support different types of spectrum users.

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 [53].

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 [54]. 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 [44]. These bands can be utilised in wired/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 [55]. In South Korea, spectrum bands in 24-27GHz and 64-66GHz have been cleared for the use in the backhaul/small cells [56]. This type of access under current classifications of the regulatory regimes falls between the individual and general authorisations in a way that 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 [54], [57]. 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 [29], [54]. Various schemes, which are defined under this authorisation regime, have been widely applied in CRNs under DSA and 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 [58], [59]. In both underlay and overlay access modes, Secondary Users (SUs) are authorised to use the shared spectrum regardless of the presence of Primary Users (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 tuning 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 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 [60].

Various enabling techniques that have been studied extensively in CRNs, comprise wide ranges of sensing techniques [61], geo-location database, beacon signalling, etc. [37], in order to enable SUs to exploit the PUs' spectrum in an opportunistic manner. Besides, for the prediction of PU activity, many theoretic models are available such as "Discrete-time Markov process", "Continuous-time Markov chain", "game-theoretic" models, etc. [34], [62]. The characterisation of access methods, which conform to this authorisation regime with their corresponding use cases are explained below.

1) Secondary Horizontal Shared Access: The licensed bands are shared by the PUs among a diverse set of SUs in a horizontal and opportunistic manner (i.e., with the low levels of access guarantees and interference protection) [63]. A number of interference avoidance schemes have also been proposed such as those in [64] and [65], to avoid interference when multiple SUs need to coexist with PUs. In this regard, cognitive techniques such as sensing, geolocation database, etc. have been applied. The TVWSs and Digital Video Broadcast (DVB) in 700MHz bands are the most common candidates to be used under this access method with lower license fees [29]. 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 [66], where for example, the white spaces are leased to SUs subject to pre-negotiation with 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 monitoring of SUs' activities. The SUs, on the other hand, select the appropriate PUs and optimal channels according to their QoS requirements, the cost of white spaces, and required channel access time.

2) 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 [41], however, low/no interference protection and access guarantees are offered. This type of access is also known as CUS [41]. 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 [29]. Such bands in Wi-Fi networks for the purpose of data offloading have been increasingly utilised [67] by 3G/4G network operators utilising their own Wi-Fi networks referred to as "Carrier-grade Wi-Fi".

The idea of extending LTE-A specifications to operate in license-exempt bands has received considerable attention recently [68]. This aims to provide seamless connectivity among "Carrier-grade Wi-Fi" and 3G/4G networks, as well as more capacity. In this approach, small cells are capable of operating in both licensed and the 5GHz license-exempt spectrum, with a primary use case known as License Assisted Access (LAA) and LTE-Unlicensed (LTE-U). License-exempt bands alongside the licensed bands are aggregated employing the same CA techniques 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 [68].

In the 3GPP specifications, LAA is expected to be launched in LTE Rel. 13 deployment. However, it is assumed that LTE 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. Although the major requirement of deployment of LTE-U/LAA seems to be installing the Base Stations (BSs), which support multi-band operation (i.e., license-exempt bands in parallel with the licensed bands), the complete specifications of this concept are not finalised yet [69]. Besides, although LTE in license-exempt bands can become a proper substitution for Wi-Fi networks in the future, in the existing networks, however, it should be ensured that the Wi-Fi users are protected from potential interference, when co-exist with LTE systems also operating in license-exempt bands [68], [70].

3) 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 allocation [29]. Under this access method there will be no costs for the license fee, however, there is no pre-defined rule(s) for interference protection and access guarantees.

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 [71]. In contrast, licensed sharing schemes provide additional licensed spectrum (e.g., for mobile use) to fulfil strict QoS demands (such as low latency, low loss rate and also guaranteed access) of services such as Mobile BroadBand (MBB).

As mentioned earlier, the focus of this article 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 Fig. 1). 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. In the next section, we discuss scenarios and use cases of licensed spectrum sharing schemes for mobile cellular networks, as well as deployment requirements from both technical and business point of views.

IV. Deployment of Licensed Spectrum Sharing Schemes in Mobile Cellular Networks

In this section, licensed spectrum sharing scenarios are introduced, and their impacts in terms of use cases and general requirements in accordance with the real deployment in cellular networks from technical, business and regulatory point of view are investigated and discussed. The detailed definition, architecture, scenario specific challenges of deployment, relevant literature, as well as open issues of both inter-operator spectrum sharing and LSA-like approaches are discussed in Sections V and VI respectively.

A. Licensed Spectrum Sharing Deployment Scenarios

Based on the discussion provided in Section III, it is evident that, licensed spectrum sharing for the mobile cellular networks is currently plausible through two different schemes. Through each scheme, different spectrum ranges can be made available. Besides, each scheme involves sharing players of various types, which introduces different requirements and challenges that have to be comprehensively investigated prior to the deployment. Due to this reason, we use the terms *homogenous* and *heterogeneous,* and introduce the classification of the licensed sharing schemes based on the characteristics of sharing players, as follows (shown in Fig. 2):

- *Homogenous sharing players:* Refers to the sharing players of the same nature, i.e., sharing among two or more MNOs can be considered as homogenous type. Obviously, the bands that are made available through these sharing schemes are the ones which have been already allocated to the MNOs. It has to be noted that, spectrum sharing between mobile operators itself encompasses various types. Multiple scenarios of *inter-operator spectrum/resource sharing* are shown in Fig. 2, and are discussed in detail in Section V.
- *Heterogeneous sharing players:* Refers to the sharing parties of different nature. Spectrum sharing schemes among non-mobile and mobile systems, whose assigned licensed spectrum bands are preferable for use by cellular systems

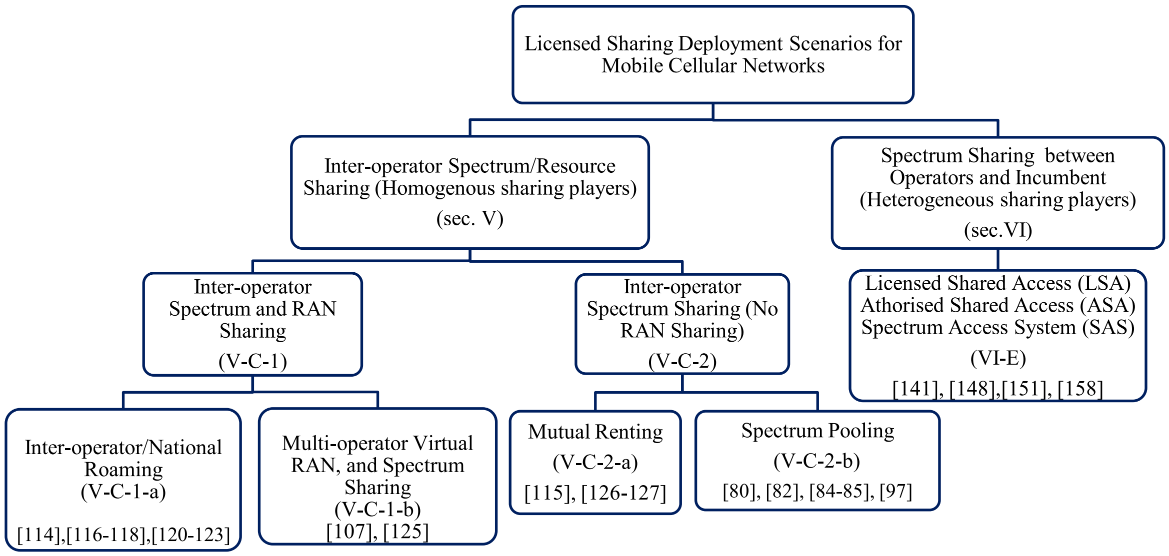

Fig. 2. Taxonomy of licensed spectrum sharing deployment scenarios.

fall under this category. The *LSA/ASA* and *SAS* frameworks (which have been recently emerged and currently target 2.3-2.4GHz in EU and 3.5GHz in the U.S.) fall in this category as shown in Fig. 2, and are comprehensively discussed in Section VI.

It is worth noting that, as the focus of this article is in mobile cellular networks, only the scenarios in which mobile operators are involved, 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.

B. The Key Deployment Use Cases and Benefits for MNOs

As *licensed spectrum* is the most valuable asset of mobile operators, 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 [68]. Thus, from the MNO's perspective, licensed spectrum sharing can provide a promising way to achieve additional capacity with *access guarantees,* as well as *reasonable QoS*, based on appropriate Service Level Agreements (SLAs). It is likely that the primary benefit of spectrum sharing will be the reduced costs compared to acquiring a license via auction. Moreover, MNOs currently own and operate on a limited range of licensed bands, thus, adapting LTE-A to operate in shared licensed spectrum can be considerably beneficial. Indeed, the key impact of *licensed spectrum sharing* is a robust and reliable capacity augmentation, which can be beneficial for many cellular network deployment scenarios such as; sub-urban/urban not-spot, urban/metropolitan hot-spot, and residential/indoor, etc. deployments.

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 [72]. The second solution is to apply 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 use and is only available in small/low capacity chunks (from 5-to-10MHz) which fail to provide consistently high 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 Fig. 2), where MNOs manage to serve their users in not-spots (national roaming is discussed in Section V). 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 Section I, 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 [18]. In the context of spectrum sharing, small cells (mainly indoor) with low transmission power BSs and low interference probability, seem to 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 operator's 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 different frequency bands. Hence, spectrum sharing in multi-RAT scenarios can provide opportunities for the MNOs who do not own RAT-specific bands, and helps improve capacity and coverage expansion (Ofcom refers this type to as partial/operator-specific not-spot [73]).

5) Capacity Enhancement Considering Frequency Division Duplex (FDD) and Time Division Duplex (TDD) Band Sharing: The feasibility of aggregation/joint-use of FDD and TDD bands in intra-operator case has been investigated in 3GPP Rel. 12 [74] specifications. Given this possibility, inter-operator spectrum sharing schemes can allow MNOs to share their bands regardless of the fact that, they are assigned to a specific access mode (i.e., FDD or TDD), resulting in capacity enhancement, as well as provisioning of wider bandwidth.

C. Deployment Requirements From Technical Point of View

Considering the suitability of the bands for mobile services (the propagation characteristics of the band are favourable for IMT), potentially all bands can be shared in condition that they cannot be cleared/refarmed, subject to international harmonisation and administrative constraints such as, temporal, spatial, and transmit power limitations. The question that emerges at this point is; what the requirements for the development and implementation of licensed spectrum sharing schemes are. In fact, the main challenge in the implementation of licensed spectrum sharing schemes, is to protect QoS-sensitive sharing players from interference, where they co-exist on shared spectrum. Failure to address this challenge results in performance degradation of sharing schemes, and therefore less incentive for sharing players to participate in spectrum sharing.

In current MAC protocols in cellular systems, where 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 User Equipment (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 Inter Cell Interference Coordination (ICIC) techniques, through an interface such as X2, adjacent BSs coordinate to avoid interference. In the context of spectrum sharing, however, when an MNO operates on shared spectrum, which belongs to another MNO or an incumbent, 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 in order to avoid interference. In the case of downlink, and when MNOs deploy their RAN in a collocated manner, or when they share the RAN, the synchronisation can be managed, to some extent. However, the problem remains in the uplink, and also when the BSs are deployed in a non-collocated manner, as the synchronisation requires fast/real-time information exchange among BSs of different MNOs via the backhaul with reasonable capacity. In fact, ICIC in multi-operator deployment scenarios require further investigations, as these techniques in the current LTE systems are only applicable for single operator scenarios, which might not be possible to extend such connection among BSs of two different MNOs [75].

In order to achieve an efficient spectrum utilisation target, a coordination among Radio Resource Management (RRM) entities, as well as micro-trading [76], and spectrum sharing enablers are required. Resource management enablers identify suitable bands that can be used, based on technical criteria and their associated quality characteristics. Micro-trading facilitates spectrum sharing based on economic criteria and cost by identifying the tradable units in the temporal, spatial and frequency domains (e.g., lower time scales) [77]. Spectrum sharing schemes provide the means for accessing and releasing/evacuating the shared bands. In licensed sharing schemes, a set of rules and regulations should be defined and agreed prior to the use of shared spectrum to secure spectrum access for sharing players and also protect against potential interference. Under such regulations, a combination of administrative and technical constraints can be specified. For instance, parameters such as the level of prioritisation, i.e., the right of access in terms of temporal, spatial, and spectral granularities, the maximum allowed transmit power, out-of-band transmitted power limits, and protection radii [78], etc., are taken into account. As a result, sharing players are subject to coordination, and therefore, the adoption of techniques which are capable to capture spectrum availabilities in a reliable manner, will be a key requirement. In fact, 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 usage level of shared bands in temporal-spatial dimensions, rather than the spectrum availability solely.

Coordination between sharing players can be carried out through various methods which are realised as "coordination" 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 inter-operator spectrum sharing and LSA, is discussed in Sections V and VI, respectively.

In general, coordination techniques can be categorised under centralised and decentralised classification, as follows,

TABLE III
ADVANTAGES AND SHORTCOMINGS OF COORDINATION TECHNIQUES FOR LICENSED SPECTRUM SHARING SCHEMES

Coordination techniques		**Advantages(+) and Shortcomings(-)**
Centralised	Database driven (e.g., geo-location database) [37], [79]	+ 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.
	Spectrum broker/ Super resource scheduler [83], [84]	
Distributed	Spectrum sensing (e.g., energy detection) [61], [37] , [33],	+ 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 [85], [86]	+ 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 [87], [88], [89]	+ 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.

and their respective implementation challenges are summarised in TABLE III.

1) Centralised Coordination: In the centralised based coordination techniques, sharing players coordinate via a central entity, so that they do not directly interact with each other [29]. The centralised techniques, which have been applied to the licensed spectrum sharing so far, are discussed below:

- *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, interference between users is calculated based on offline (none real-time) theoretical propagation models, which allows promising interference protection [37]. This technique is widely applied in the case of TVWS sharing, and also in the LSA reference system architecture.
- *Centralised management entity:* The techniques such as super resource scheduler, meta-operator, and spectrum broker, 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 (which is discussed in Section V).

The implementation of such centralised techniques 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 central entity and sharing players, and also the management of this entity itself, are the least requirements of such coordination protocols. On the other hand, from a security point of view, preserving confidentiality of spectrum usage status, is a critical concern for stakeholders (typically actual spectrum owners) in centralised-based coordination techniques [79]. 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 [80]. Moreover, in such coordination techniques, 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 (e.g., over the air signalling). Signalling information can be transmitted using the wired backhaul, subject to the economic consideration of the deployment. 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. Nonetheless, massive demand for non-line-of-sight backhaul is still inevitable. 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 [11]. 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, this issue should be potentially considered in order to minimise the burden of overhead to facilitate management of such centralised-based coordination approaches.

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 (inter-operator spectrum sharing and LSA) with highly dynamic traffic demands. This technique, however, can be applied in the case of TVWSs sharing [81], [82], to deliver MTC services with rather static spectrum usage pattern and fixed transceivers' position.

2) 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 licensed spectrum sharing so far, are discussed below:

- *Spectrum sensing:* By the aid of sensing techniques, devices (e.g., BS or UE) can detect the presence of other devices operating on shared bands, prior to transmission to avoid interference. A wide range of sensing techniques are available, ranging from; energy detection, feature detection of co-existence beacons [61] etc. Applying sensing techniques, the detection is performed on-demand and in a dynamic manner, hence, other parts of the system are not required to be involved in this technique (in contrast to the centralised coordination techniques). However, reliable detection of the idle bands is subject to the system complexity and increased costs of enhanced sensing/measurement techniques [33]. Multiple threats affect the PHY, such as malicious node attack and in the MAC layer, the hidden node problem, and sub-optimal false alarm and detection probability issues [79]. Besides, the time duration which is required to perform sensing and detect the idle channel, leads to the reduction of the effective data transmission time (i.e., a trade-off between sensing time and data transmission time) [61], [90]–[92]. The currently available distributed sensing techniques are not typically considered as highly reliable methods [33], to be applied for the licensed spectrum sharing schemes. This problem will be concerning more specifically in the cases where the sharing players are different in nature and have strict interference avoidance regulations (e.g., LSA case). In [93], a comparison of advanced cyclic prefix-based sensing techniques is carried out, indicating that, under realistic channel models and assumptions, a probability of detection of 90% is achievable at SINR roughly -10 dB, which falls short of the desired targets, e.g., those set in [94]. 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 [61], [95]. 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 [37], [47].
- *Coordinated beamforming:* Beamforming techniques enable 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 [85]. In the context of spectrum sharing, beamforming techniques facilitate co-existing multi-technology deployments. However, the coordinated beamforming is subject to the sharing of CSI and even of user data between sharing players in order to avoid inter-system interference. This is realised as the main concern in real-world deployments of this technique in licensed spectrum sharing schemes [96].
- *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 [34], [89], [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.

D. Deployment Requirements From Business Point of View

It is reasonable to expect that the deployment of spectrum sharing introduces economic and business concerns to the stakeholders. This can comprise the costs of additional infrastructure, probable required modifications of the existing systems to support and manage the sharing procedure [71], 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. In fact, there is a trade-off between the costs and benefits of spectrum sharing, that stakeholders must weigh the corresponding costs, and assess whether the sharing is worth the investment to achieve the claimed benefits.

The main known business concerns associated with the deployment of licensed spectrum sharing 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), has 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 operators, whereas the practical backhaul rate for one cell in a dense urban scenario and also one site is almost 100Mb/s and 300Mb/s respectively [75]. 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. For instance, in the case of heterogeneous sharing scenarios, such as LSA, new administrative sites, are required to monitor the situation, process and restore the information. 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 [54]. In the case of homogeneous sharing scenarios (e.g., inter-operator sharing), the concept of infrastructure sharing as a complementary scheme is currently supported in 3GPP specifications [100], and is expected to result in savings the costs considerably. Moreover, the real deployment of spectrum sharing may require across countries and continents coordination to avoid cross-border interference [101].
- *Multi-band operational capabilities:* The support of new frequency bands requires software modification 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. Increasing spectrum bandwidth requires increased processing power, especially for the PHY layer processing and the complexity is known to be increased linearly with the spectrum size [75].
- *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 inter-operator spectrum sharing, 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.
- *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) [101]. 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 [102], and spectrum leasing [66]. However, more reasonable pricing policies are required to incentive sharing players to participate in spectrum sharing.

As the main focus of this paper is on the technical aspects associated with spectrum sharing, the business impacts are not studied comprehensively. 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 [54], [84], [101], and [103].

E. Summary

To summarise, it can be concluded that each coordination scheme is applicable to the scenarios characterised by different demands. The centralised approaches, typically without the need for UE involvement, are simpler to be controlled, and provide more reliable and fair allocation of spectrum. However, there is a need for additional network infrastructure and result in considerable amount of signalling overhead for coordination between sharing contributors, especially the ones with dynamic varying traffic load, and therefore dynamic spectrum usage. Besides, the latency in such schemes matters, when the real-time traffic is transmitted due to the fact that coordination with the central entity requires additional time. In distributed schemes, 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 between competitive sharing players, which is less favourable for them to share their spectrum usage information and sometimes user data. In fact, the sharing schemes in simulation studies need to be evaluated under realistic assumptions, in order to establish the performance gains, and identify potential business level enhancements, prior to the deployment, so that they incentive the stakeholders 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). In the following sections, the SOTA implication of the aforementioned coordination techniques in various sharing deployment scenarios (shown in Fig. 2) is investigated and discussed in detail.

V. Inter-Operator Spectrum/Resource Sharing (Homogenous Sharing Players)

A. Overview of Inter-Operator Spectrum Sharing

In inter-operator spectrum sharing schemes, sharing players are of the same nature, i.e., they employ similar network infrastructures, deliver similar types of services to the customers, and therefore, have the same system/performance requirements and sensitivity. In such schemes, mainly asymmetric traffic fluctuations among MNOs are taken into account to determine the amount and time duration of idle *spectrum* for the purpose of sharing. Apart from the spectrum, due to the heterogeneity of the sharing parties, there is an opportunity of *network sharing* among the MNOs with limited support in the 3GPP specifications (LTE/LTE-A) [104], where network resources (infrastructure) such as Core Network (CN) node, and RAN can be shared along with spectrum [100]. Network sharing between operators 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 Fig. 3 [105]. 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 [106], [107].

Network sharing can take many forms, ranging from passive sharing up to active 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 [105], [108]. It can also involve fully integrated models such as, Multi Operator Radio Access Network (MORAN), Multi Operator Core Network (MOCN), in which, the RAN is shared, and gateway core network, in which both RAN and some parts of CN node are shared. The adopted model, 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 U.K. has implemented a pro-active approach to network sharing for a long time. More details of the architecture and functional requirements associated with these models can be found in [27].

B. Regulatory Approaches Towards Inter-Operator Sharing

From the regulatory body's point of view, inter-operator resource sharing can have considerable impacts on efficient resource utilisation. It can contribute on the efficient competition at the market to promote consumer interests (e.g., cost and available of services) [109]. For example, in South Korea, the telecom regulator has put a lot of efforts into promoting competition by developing policy relevant for inter-operator resource sharing. In 2010, the regulator enacted the telecommunications services wholesale regulation, called as the Mobile Virtual Network Operator (MVNO) act to let MVNOs enter the mobile telecommunications service market [110]. Due to MVNOs entry, the mobile telecommunication service market was expected to become more competitive. However, since the market is mature and most of the users are subscribed with incumbent MNOs, the MVNOs have had difficulty in achieving their own market share. 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 (for another year until September 2016). In addition, the regulator is preparing for allowing a new MNO to enter the market. In order to reduce a new MNO's entry barriers, the regulator has prepared for policies including national roaming, reserved spectrum, and interconnection fee [111].

Since the current regulation considers the nationwide licenses for mobile operators, a new entrant is expected to build its own network before launching its business. However, the regulator has developed a national roaming policy so that a new entrant will have time to deploy nationwide networks. According to the regulation, 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. In addition, the regulator is considering reserving spectrum for a new entrant in an upcoming auction [112]. For the interconnection fee, the regulator has also put in place policies to give advantages to a new entrant.

The *inter-operator spectrum & RAN sharing* approach has been implemented in many countries (in the context of *international roaming*), however, *inter-operator spectrum sharing*

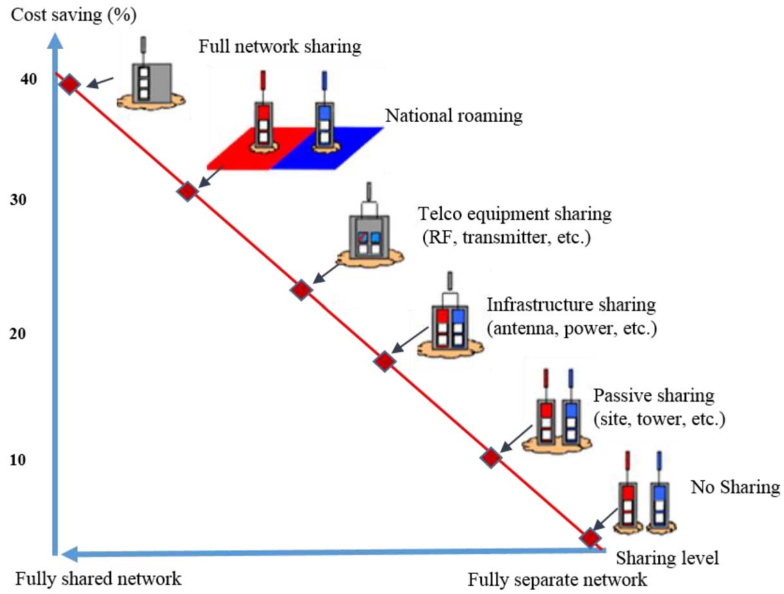

Fig. 3. Network sharing models and corresponding cost saving gains [105].

approach 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 from the operators' perspective are of great importance, rather than the regulator's perspective.

C. Inter-Operator Sharing Scenarios and Related Work

Based on the aforementioned sharing options, the different sharing scenarios with different technical and business concerns (e.g., mobility management, interference management, inter-operator coordination, security, charging, etc.) are identified [104]. In this regard, various inter-operator spectrum sharing scenarios have been proposed and discussed in the literature. However, due to the business concerns and lack of strong evidence in favour of sharing and associated gains, the MNOs have not shown willingness to proceed for the practical deployment so far [11], [113]. The emerging demands for more capacity, and on the other hand, the potential role of spectrum sharing towards addressing the problem of under-utilisation of the licensed bands in future cellular systems, have resulted in increasing interest in the investigation of inter-operator spectrum sharing schemes for the real-world deployment.

In the following sub-sections, we study the existing proposed sharing schemes in the literature (which incorporate coordination techniques described earlier), in terms of achieved gains, as well as the deployment challenges, based on the classification we introduced and showed in Fig. 2, i.e., *1) Inter-operator RAN and Spectrum Sharing* and, *2) Spectrum Sharing (no RAN sharing)*. In terms of MNOs' RAN deployment, we consider two different deployment scenarios where MNOs are either *collocated,* having the same cell coverage or *non-collocated*, covering different areas (where cells of different MNOs might partially overlap) [106]. It should be noted that the scenarios related to the CN node sharing are not addressed in this article.

1) Inter-Operator Spectrum and RAN Sharing: Given above, this sharing model is categorised as; *a. Inter-operator/National Roaming*, when MNOs provide coverage in different geographical areas (i.e., exclusive RAN deployment), and *b. Common Spectrum and RAN Sharing*, when two different MNOs cover the same geographical area. More detail is discussed below.

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 known as inter-operator handover). This is typically performed by the UE, which measures the signal strength of the pilot signals (beacon signals) of the neighbouring BSs and consequently will be connected to the BS with the strongest pilot 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 areas (which may partially overlap), which is carried out based on agreements [115] among the MNOs. In the case of national roaming, interference and mobility management of the involved UEs are straightforward and less challenging, as UEs 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. However, for the UEs, which are located in the partially overlapped coverage areas, additional consideration and negotiation among the MNOs are required [104]. In Fig. 4, the network topology, as well as information exchange procedure of this type are shown. The relevant literature pertaining to inter-operator roaming is discussed below.

In [114] and [116]–[118], inter-operator roaming is implemented. In this regard, inter-operator roaming is carried out subject to the spatial-temporal spectrum usage/availability of

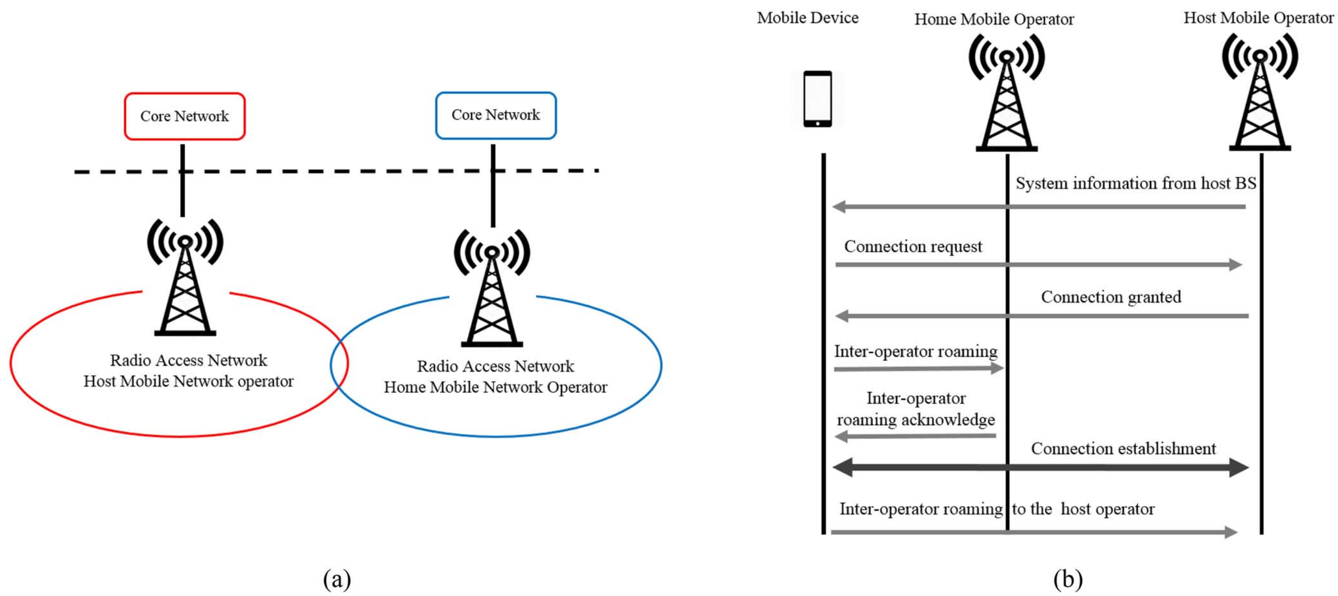

Fig. 4. Inter-operator/National Roaming (a) Network topology, (b) Connection setup information flow [104], [114].

the participating MNOs (with exclusive and non-collocated RAN deployment) in spectrum sharing, given that they always prioritise their own users to serve (primary-secondary hierarchy). This implies they take advantage of asymmetric traffic peaks of the operators. However, different coordination techniques are applied in each approach, and the impacts of sharing in various systems are evaluated.

In [116], the authors consider shared RNC as a centralised coordination entity for the management of sharing between two MNOs operating in wideband Code Division Multiple Access (CDMA). The system performance is explored for two different cases comprising equal and a non-equal amount of spectrum of the MNOs. It is stated that, although the busy hours of MNOs are typically the same, this does not necessarily mean "that traffic patterns" during busy hours are also exactly symmetric. Hence, even if both MNOs have equal amounts of spectrum, still limited sharing gain (5% to 20%) in terms of additional capacity can be achieved due to instantaneous uncorrelated traffic patterns. The second case though, i.e., when MNOs own non-equal spectrum chunks, sharing can result in better performance (32% improvement in cell capacity shown in this approach). However, the achieved gains stop increasing when the capacity demand by PUs increases and the primary MNO is no longer able to serve SUs.

In [114] and [118], a UE performs handover/roaming to the RAN of adjacent MNO (operating on Universal Mobile Telecommunications System, UMTS), in a distributed manner, taking advantage of cognitive sensing techniques without the presence of any centralised controller (such as shared RNC). The results show 9% throughput improvement compared to the case of Fixed Spectrum Allocation (FSA). However, the signalling overhead, due to the inter-RAN messaging, decreases the achieved gain (effective throughput in this work). Besides, the connection setup delay (i.e., when the UEs perform inter-RAN handover to the other participating MNO), is considered as a negative aspect of this approach which is expected to be decreased if RNC is shared between the MNOs.

A comprehensive comparison of the results of above mentioned approaches is provided in [117] and [119]. The authors conclude that the gain is achieved through such schemes highly depends on the degree of the traffic load correlation among the MNOs (i.e., the symmetry of load). Thus, higher traffic correlation (which has been investigated in this work from 80% to 100%) leads to lower/no gain. Almost all of the aforementioned sharing schemes are evaluated for only voice traffic, however, today majority of real-time services (e.g., MBB) are known as high priority candidates (rather than typical voice) that must be taken into account where spectrum sharing is expected to help provide wider bandwidth. In this respect, the impact of probable delay (due to the required coordination between the operators prior to access to the shared bands), on the QoS of MBB services would be a valuable factor to estimate whether a sharing scheme can be practically deployed.

In [120]–[122], a similar network topology is considered, where a centralised resource scheduler, as a meta-operator is applied to manage the sharing procedure. The MNOs operate on their own RAN with non-collocated BSs (all operating on the same RAT). Users are assumed randomly distributed over the entire network being able to connect to any BS regardless of the MNO (i.e., either home or host MNO). It is also assumed that MNOs are completely synchronised, and therefore, the impact of interference among BSs is considered negligible. The approaches, however, are distinguished based on the applied sharing policies which are described below.

In the first approach [120], the decision is made based on the distance between the UE and the BS along with the received signal strength, so that the UE is *always connected to the nearest BS*. In the case that the nearest BS is overloaded, UE is scheduled to connect to the next nearest BS. In the second approach, however, sharing is carried out as a *last resort*, i.e., each MNO allocates its exclusive bands only to its own UEs. The centralised scheduler keeps track of the load of the BSs, and searches for empty slots/spectrum in other BSs regardless of the MNO's ability to serve the UEs of the overloaded BSs. The results show that both "*always connected to the nearest BS*" and "*sharing as a last resort*" achieve improved performance in terms of delay for different types of traffic, such as voice and video, of almost 98% and 83% respectively, compared to the non-sharing schemes. It is also stated that if the number of MNOs increases, the capacity improves (more shared spectrum becomes available). However, it should be noted that increasing the number of MNOs in such sharing schemes results in the need for more cooperation among MNOs. The interference management among BSs (which has been ignored in this work), finding the appropriate BS to serve the UE, by a central management entity, imposes a high signalling load and increases the delay, and therefore, degrades the overall system performance. In [122], the authors believe that applying the aforementioned sharing schemes are more beneficial for the services with low to moderate required data rate, e.g., *Web* and *file transfer*.

In [123], it is stated that due to the complexity and cost of information exchange procedure for coordination among MNOs in fully centralised schemes and also of building a CRN to sense the idle spectrum in fully distributed schemes, spectrum sharing has not been practically applied so far. Hence, a partially distributed algorithm based on GT and learning coordination technique is proposed, so that a lower information exchange among MNOs is required. For coordination among MNOs vertical handover is considered, allowing each UE to connect to any available BS irrespective of the MNO. In this work, the problem of synchronisation of the participating BSs (particularity in LTE specifications) with asynchronous information broadcasting is considered as a challenge in the case of inter-operator roaming. A queueing technique is proposed to manage the coordination of asynchronous MNOs. A gain of roughly 30% is reported in terms of capacity improvements.

It has to be noted that the practical implementation of national roaming, faces a number of technical issues, commercial concerns, and operational complexities. For instance, limitation on the number of sharing contributors and also concerns of host operators on whether they will have enough spectrum to accommodate their own users, are some of the issues that are investigated by the regulatory bodies such as Ofcom. On the other hand, in terms of "user's experience", the seamless connectivity must be guaranteed in inert-operator roaming. In this respect, the traffic prioritisation is suggested so that high priority types of services such as voice to be delivered. Besides, in the case that multiple operators are involved in national roaming, an appropriate policy should be defined in order to avoid constant network re-selection and signalling overhead to a specific network [124].

b) Multi-operator virtual RAN, and spectrum sharing (common spectrum and RAN sharing): In this sharing scenario, two/multiple operators share a common RAN (i.e., RNC and BS), in the same geographical area, which is connected to separate CN nodes belonging to the respective operators. Operators may also share part/full spectrum bands.

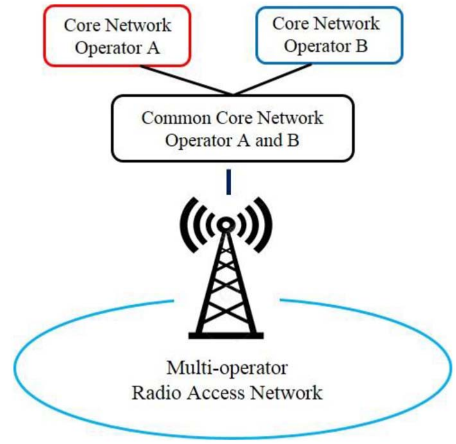

Fig. 5. Multi-operator RAN topology (common spectrum and RAN sharing) [104].

This scenario is known as virtualised RAN and spectrum sharing, and enables the deployment of virtualisation in cellular networks with subsequent support for MVNOs [105]. The advantages of the RAN sharing, such as considerable cost saving, discussed earlier in this section. The reference/high level network topology [104] is depicted in Fig. 5. The relevant literature pertaining to virtualisation is discussed below.

In [107], the concept of *CellSlice* is proposed and investigated. The main focus of this method is to achieve the most efficient gain of RAN sharing for shared spectrum allocation among users, with minimum modifications to the existing BS. The term *Slice* is referred to a group of users belonging to a single MNO that requires a portion of the spectrum to be able to transmit data. *Slicing* is defined as resource allocation mechanism for the slice. Slicing procedure is carried out at the Serving Gateway (SG) level rather than a BS level (the resource allocation is currently carried out by the scheduler in the BS and the SG has no sense of the traffic load), in order to avoid queueing and keep fair allocation and isolation among flows (slices). However, this work is a proof-of-concept prototype design and further studies and investigations are being carried out to explore the possibility of the practical deployment of such methods.

In [125], multi-operator virtualised RAN is managed by a centralised controller in a network level which monitors the sharing procedure and coordinates with the Mobile Management Entities (MME) of two MNOs. The spectrum is shared only when an MNO is overloaded in a specific cell and sends a request to the centralised entity. The performance improvement is shown in terms of reduced packet drop probability in virtualised networks compared to the spectrum sharing. In this work, it is concluded that, shared RAN can be highly beneficial compared to the case of spectrum sharing (which is addressed in the next sub-section), 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, virtualisation scenarios impose additional costs in the system to support virtualisation capabilities, such as software/hardware reconfigurable radio frequency frontends.

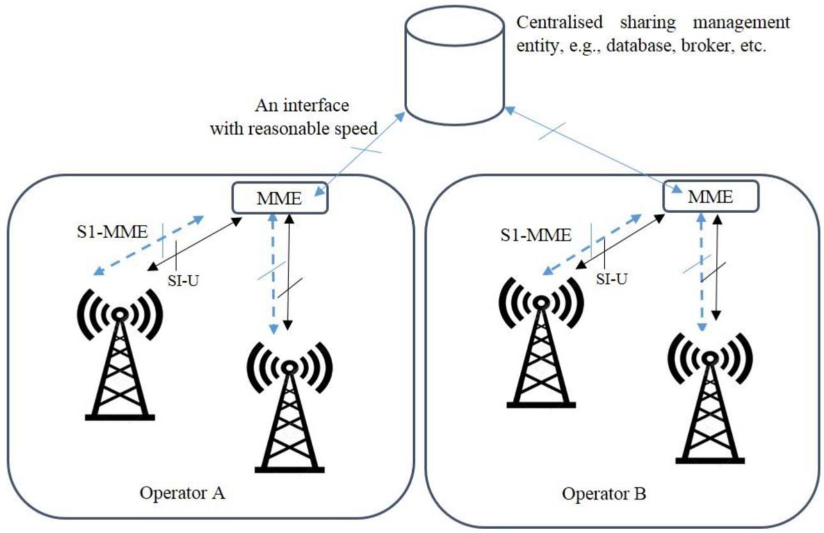

Fig. 6. Inter-operator coordinated mutual renting via central third-party entity [125].

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) [11]. This sharing scenario is also referred to as *Co-Primary Spectrum Sharing (CoPSS),* and is classified as; *a. Mutual Renting,* and *b. Spectrum Pooling,* (see Fig. 2) where both conform to the aforementioned access modes in the *individual authorisation* in Section III. We next describe the system requirements for this type of sharing and then, the discussion of related work according to the literature for *mutual renting* and *spectrum pooling* are presented respectively.

a) Mutual renting approaches: The concept of *mutual renting* was explained in Section III. This type of spectrum sharing is similar to the interweave approach in CRNs, i.e., exclusive shared spectrum access where no interference is tolerable and almost always the actual owner of the spectrum (who is referred to as *host* operator) has the priority to access the band [57]. However, in contrast to the CRNs interweave approach, and based on the agreement among operators, access to the spectrum as well as QoS must be guaranteed for both sharing players. An exemplary case of this type is; when the host operator owns RAT-specific bands (e.g., 3G license) and shares this spectrum with other operators (referred to as *guest* operators), who do not own the bands.

The main concern, in this type, is to find an efficient and reliable way for the guest users to detect and access the free spectrum while protection of the users of the home operator from interference is highly taken into account. In this respect, when the BSs of different MNOs are collocated, interference management is rather straightforward, as due to the binary nature of spectrum access (either the *home* or *guest* operator can utilise the spectrum at the same time/location). In the non-collocated case, however, the interference occurs when the BS of the guest operator negotiates with the adjacent BS of the host operator regarding the channel availability and, if permitted, allows its users to access the shared bands. In that case, users moving across the cell may cause interference to those users of the host operator who are using the same bands in adjacent cells, risking corruption of the frequency re-use pattern of the host operator. Hence, the BS belonging to the guest operator might need to coordinate with multiple adjacent BSs of the host MNO to avoid interference, which is not the ideal solution [125], [126]. 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 operators is depicted in Fig. 6.

In [127], the authors apply cognitive sensing through energy detection as a coordination technique (which is performed by UE or any other sensing equipment) between two MNOs. The primary-secondary priority right of access to the shared bands is considered as spectrum sharing policy between participating MNOs. The asymmetric traffic load of the MNOs is to account, so that if one MNO is lightly loaded, the other MNO can exploit the shared spectrum in the absence of the actual owner of the band to avoid interference. The accurate spectrum availability detection as the main challenge of this approach (when sensing technique is solely applied) is studied with respect to the time scale of the sharing among the MNOs. The spectrum is shared from a unit of sub-frame to several frames. Two different time scales are discussed in this work are as follows.

In the first case, sharing is agreed for the several hundreds of frames. The BSs of two MNOs negotiate via the backhaul to perform sharing. In this case, one BS can be switched off when the BS of the other MNO is operating in the shared bands. Thus, sensing is not required, as it is guaranteed that no other MNO transmits over the shared carrier.

In the second case, however, sharing is performed on a smaller time scale, e.g., tens of frames or even in a single sub-frame level. In this case, due to the short time duration of sharing, it does not seem to be reasonable idea to switch off the BSs as they need some additional time for the transmission of synchronisation signals, control channels, etc. Two types of sensing are proposed and applied to detect the interference signal, on a particular Physical Resource Block (PRB) to detect vacant channel for transmission. However, there are some constraints in the structure of control channels in LTE systems, when sharing is performed at the sub-frame level and sensing is applied. As the PRB allocation varies in every Transmission Time Interval (TTI), there is always the possibility that a PRB which is recognised free, is occupied in the next subframe making the sensing result from the previous subframe invalid and results in collision. When two BSs, belonging to different MNOs, transmit through a single PRB during one TTI, the Physical Downlink Control Channel (PDCCH) [128] of two BSs which is transmitted via specific Orthogonal Frequency Division Multiplexing (OFDM) symbols of that PRB, will overlap in the same symbols. This problem can be solved via either synchronisation between the BSs, or cross-carrier scheduling (which means that each MNO must have a dedicated spectrum in parallel with the shared spectrum) ,or applying LTE Rel. 11 feature, e.g., [127] in which, the control data can be transmitted in any OFDM symbol. Given the challenges of the deployment, this approach can be deployed as a complementary trend in conjunction with other approaches.

In [115], the authors propose a spectrum sharing scheme among the small cells of two MNOs, via a distributed coordination method. It is stated that the centralised coordination among MNOs requires noticeable amounts of information exchange through the backhaul. Hence, in this approach, spectrum occupancy information is broadcasted by the small cell BSs, using the same control channels that are used for generic system information and is updated periodically. The sharing policy is based on the priority of access for the actual spectrum owner. The performance of the approach is evaluated in both asymmetric and symmetric density deployments of small cells of two MNOs. In the case of symmetric density deployment, where both MNOs own equal number of small cells, the achieved average cell throughput and average user throughput gains around 7% is achieved in terms of cell-edge throughput and average user throughput compared to FSA. Although the results show improvements, the respective security aspects of this approach should be explored to find whether MNOs would agree to broadcast their channel occupancy information across the network to be accessible for other operators.

The deployment of Wireless Sensor Networks (WSNs) is investigated in [126], in order to capture shared spectrum availabilities in a more reliable manner compared to the case that sensing is performed by the UEs (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 on a real-time basis, such as noise, interference, and location information of the transceivers in the mobile cellular networks. Sensors are connected and cooperate via wired or wireless links to exchange information about the spectrum usage across the entire network. They can be shared between several MNOs so that the BSs belonging to each MNO in a specific area can communicate with the corresponding sensor node. 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 requires further considerations.

b) Spectrum pooling approaches: The concept of *spectrum pooling* was explained in Section III. This sharing method can be deployed in either a cooperative (real-time coordination among MNOs) or non-cooperative (non-real time coordination among MNOs) manner. Due to the simultaneous utilisation of the shared bands by the MNOs, the probability of interference can be relatively high. Therefore, either a tolerable level of interference must be agreed among participating MNOs prior to utilisation of shared bands, or a robust coordination protocol is required, to manage sharing procedure. A vast majority of the approaches related to this type of sharing have been proposed, which some of them are discussed below. These schemes are distinguished by their different network topology, the policy of shared spectrum allocation, and applied coordination technique. An exemplary type of this sharing method is depicted in Fig. 7. The relevant literature pertaining to spectrum pooling is discussed below.

A CoPSS scheme for small cells is investigated in [45] and [129], when two MNOs agree to share a certain number of component carriers on a pool basis. The signalling overhead of point-to-point coordination among the participating MNOs for interference protection (while utilising shared bands simultaneously), is believed to be the main concern in CoPSS scenarios in this work. Therefore, the concept of self-optimisation and self-organisation is applied on a cognitive distributed manner to minimise the level of required coordination among MNOs in [45]. Besides, an additional entity, which is called *spectrum controller,* is introduced in each MNO's network, which is responsible for the management of the spectrum sharing procedure. The small cells send the interference level of their UEs to the controller. Based on this information, the controller distributes the shared spectrum to the small cells, resulting in only small cells with lower levels of interference being able to use the shared spectrum. The system performance in terms of system throughput and cell edge throughput shows improvement, compared to the two different spectrum allocation schemes defined in this work as baseline scenarios. In the first case, both MNOs are considered utilising the spectrum pool at the same time without coordination, and in the second case, the spectrum pool is divided into two orthogonal parts, so that each MNO is permitted to utilise only its allowed spectrum portion without causing any interference to each other. The authors state that spectrum pooling schemes seem to be more applicable to indoor small cells (as clusters of small cells are likely to be more geographically separated/isolated than larger cells) and shared use of spectrum by MNOs can result in lower level of interference.

This method implies that eventually, additional spectrum is required to send the control data to the controller and receive the results of the decision from it. Besides, in this work, small cells and macro cells are assumed to operate in different bands and the impact of large cells and small cells on each other in

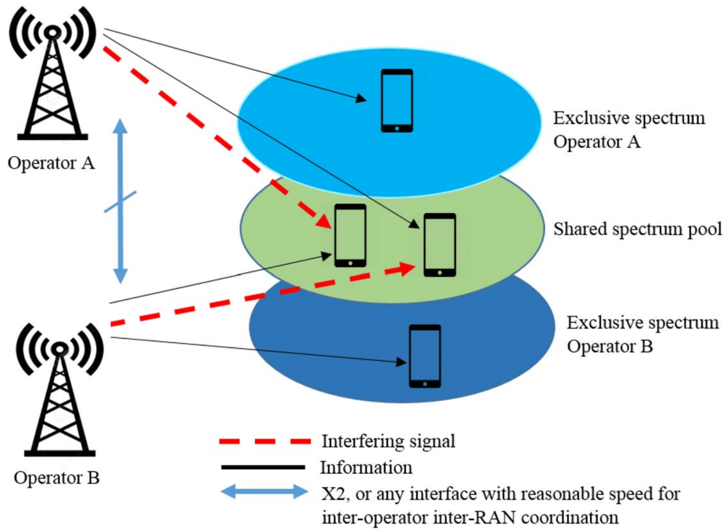

Fig. 7. Multiple operators' transmission on a shared spectrum pool through beamforming techniques [86].

terms of interference is considered negligible. Thus, the performance of this approach should be examined when both large cells and small cells operate in the same bands, as operating in individual bands degrades the main goal, which is the most efficient use of spectrum.

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* to assure exclusive access to the shared spectrum to avoid inter-operator interference. The centralised entity is assumed to have a connection with the respective BSs and allocates the shared bands in a mutually exclusive way to the UE with the best Channel Quality Indicator (CQI) in order to achieve the maximum cell capacity. Thus, no fairness criteria are to account. The performance of this approach for both asymmetric and symmetric traffic loads is discussed for varying percentages of sharing ranging from 0% to 100%. In both cases, 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 MNOs and the corresponding central entity requires additional resource. Besides, the scalability of such scheme in the case of multi-cell/multi-operator deployments should be evaluated.

In [130], the spectrum is shared on a pool basis among two MNOs operating on CDMA systems, the same RAT (UMTS in this work) and owning exclusive RANs. In CDMA systems, when BSs of different MNOs use the same carrier at the same time but exclusive code, they need to be synchronised to maintain the code orthogonality in order to avoid interference. Hence, accurate coordination protocols among MNOs should be applied to preserve orthogonality and achieve the optimal result of sharing. Therefore, the further two BSs of different MNOs are from each other, the harder it becomes for them to be synchronised. The impact of displacement on the performance of spectrum sharing is investigated in this work. The achieved gain decreases with the increase of the distance between two BSs. The capacity gain achieved in the best case, i.e., for separation distances of up to 300m, is 7% and for large separation distances, e.g., 650m, there are reported capacity losses of up to *-20%*.

A cooperative CoPSS scheme among two collocated MNOs (sharing the same cell site), which operate on their own RANs, is proposed in [131]. A spectrum pool including dedicated spectrum for each MNO (orthogonal) as well as the shared spectrum (non-dedicated/non-orthogonal) is considered in a way that the allocation of the spectrum from the pool adaptively varies. The adaptation is performed by the scheduler that takes the channel conditions of the users into account. In that sense, if a user has low signal strength due to inter-operator interference, it will be served on dedicated spectrum, otherwise, the shared spectrum is assigned. Coordinated beamforming technique is applied and MNOs share their inter-RAN CSI via fibre optic-based backhaul as they simultaneously may need to use the shared band. Also, an inter-RAN precoder is applied to minimise inter-operator interference. Some performance improvement is shown in terms of the average user throughput compared to the case of fully dedicated use of spectrum (i.e., non-sharing) and aggressive use of fully shared spectrum with a high level of interference among MNOs, as a function of macro-cell inter-site distance. The improvement is achieved for the users located in the centre of the cell with higher signal strength.

In [132] and [133], the authors explore the case that, the whole spectrum pool is available for simultaneous access of two MNOs in the same area, while beamforming as coordination technique is applied (see the relevant network architecture for this coordination technique in Fig. 7). As mentioned earlier, the major issue of applying beamforming techniques is CSI that needs to be shared among BSs of different MNOs as well as interfering CSI among BSs of one MNO and UEs of the other MNO. 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 that the channel response can be considered flat [132]) and with sufficient accuracy to get the best result of the beamforming technique. In this work, also it is stated that although full band sharing allows the MNOs to receive double bandwidth, more spectrum is used to suppress interference. Given the performance evaluation results, a rather limited gain can be achieved through this coordination technique. The results are explored only for one user per MNO and in terms of multiuser diversity, the achieved gain is expected to be even lower. Apart from the technical side issues, this fact also should be taken into account that, the operators are not willing to share their operator-specific information such as load, channel usage, or CSI. This implies that, the implementation of beamforming for the purpose of sharing requires further enhancements to minimise/avoid the level of information exchange among the MNOs.

GT as a coordination protocol is applied in [87], called "non-cooperative repeated game". In non-cooperative GT based approaches, the sharing players do not need real-time interaction, and thus, make decisions independently [88]. The interaction between two MNOs is performed in a top (network/SLA agreement) level rather than RAN level, with the purpose of reducing the signalling, as well as to avoiding operator-specific information exchange between two MNOs. In this approach, the history of previous interactions between two MNOs are exploited to define a threshold in order to determine when one MNO is expected to ask for shared spectrum or, in reverse, it is able to offer spectrum to the other MNO. The performance of this approach is evaluated for small cells of two MNOs in the same coverage area, and the results show improvements in term of provisioning higher data rate compared to the non-sharing case. This approach, however, considers only the case of asymmetric traffic load and no discussion on how this approach will be able to perform in the case of symmetric traffic load of both MNOs which is a more realistic case, in provided (specifically in spectrum pooling scenario where both MNOs have the same right of access to the pool of spectrum).

In [134], multiple MNOs share a pool of spectrum (component carriers are shared in this work) in a decentralised manner for indoor small cells applying *learning* techniques. Through this sharing scheme, it is aimed that the MNOs exploit the shared spectrum without the need for coordination and exchanging information between them during the sharing procedure. Similarly to the other pooling based schemes, the interference and fairness as inevitable challenging facts, are considered in this approach. In this respect, a utility function is proposed, which performs based on a learning technique so-called "Gibbs sampling". Based on that, the MNOs choose suitable shared bands based on "estimated average rate" of each small cell BS (UE maybe is involved in estimation) in order to achieve their "target data rate". Besides, a pre-agreed allowable shared spectrum ratio, and time of using the shared bands are identified, from the fairness perspective. The performance of this approach is evaluated and compared with three other cases; non-sharing, "Greedy" (when operators exploit the shared bands without following any rule) and "Equal" (when operators obtain an equal amount of shared band in an exclusive manner without interfering each other).

The results show that the achieved gain, even in the best case scenario (where target data rate of only one MNO is considered high and target data rate of others are assumed low), is very limited and "Equal" method still outperforms. Such result implies that more efficient coordination protocols yet to be investigated and proposed.

In [135], authors investigate spectrum sharing for small cells when a pool of shared spectrum is provided by the MNOs who have unutilised spectrum and each MNO can specify the percentage of spectrum is willing to share. The coordination between MNOs is managed by a centralised controller which collects the spectrum occupancy information from the small cells' BSs, and follows different shared spectrum allocation policies such as "random" or "equal" allocation among overloaded BSs. The sharing procedure is performed in PRB level which in this work is stated that it ensures more efficient utilisations of spectrum compared to component carrier level, but would be more challenging due to the required "synchronisations" between operators. It is stated that the UE is not aware of spectrum utilisation in the pool and it may fail to calculate its SINR and CQI over the shared PRBs accurately, and therefore, ends up interfering other UEs. A distributed approach is also proposed, where all the adjacent BSs participate in sharing, must to be inter-connected in order to inform each other about shared spectrum utilisation, to avoid co-channel interference.

Given the fact that MNOs are hesitant to share their operator-specific information, such as spectrum availability, this approach may fail to attract the MNOs to apply this sharing mechanism in their network. The performance of the proposed approaches is evaluated under low traffic load (for full-buffer traffic) in both collocated and non-collocated network deployment scenarios, and limited gain has been achieved. It is stated that, under high traffic load (when there is no free PRB), the gain is nearly zero. Besides, the impact of coordination is investigated for different traffic types, as well as various sharing percentages, which is shown to be effective so that the system throughput with coordination compared to non-coordination avoids the system throughput losses.

D. Summary

The SOTA licensed spectrum sharing scenarios studied in this section. To summarise, in can be seen 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 CoPSS schemes (comprising mutual renting and spectrum pooling approaches), it is observed that, lack of efficient coordination schemes results in CoPSS 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 user is located close to its serving BS with reasonable signal strength in outdoor scenarios, 3) where traffic/capacity demand asymmetrically varies among sharing players, so that

TABLE IV
SUMMARY OF THE SOTA APPROACHES FOR INTER-OPERATOR SPECTRUM SHARING

Deployment scenario	Spec./incorporated coordination tech.	Advantages (+) and Shortcomings (-)	Ref.
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	[114]
	=> 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	[116], [140]
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	[107], [125]
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	[127]
	=> 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	[115]
	=> 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	[126]
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	[83]
	=> 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	[15], [85], [133]
	=> Game-theory based approach => Cooperative games performs based on pre-sharing agreements among MNOs	+ No need for real-time inter-MNO information sharing - Efficient and fair policies are complex to implement	[87], [88], [97]

they have some spare spectrum to share. This problem limits the gain can be achieved through spectrum sharing, and results in a lack of interest to proceed for the real-world deployment [125]. In this respect, efficient sharing schemes with robust interference protection mechanisms and minimum possible information exchange/sharing among the participating MNOs are required. A summary of the discussed approaches is presented in TABLE IV.

VI. LICENSED SHARED ACCESS (HETEROGENEOUS SHARING PLAYERS)

As mentioned earlier, the demand for *licensed sub-6GHz* bands has led to competing environment among various spectrum users, including mobile cellular networks. It has been observed that parts of exclusively allocated licensed bands (to the incumbent systems) remain significantly unutilised at some locations or periods of time. Based on the results from measurement campaigns in various locations across the world, the average spectrum utilisation percentage of some spectrum bands was found to be low in various deployment scenarios [23]. For instance, the measurements show that 54% of the spectrum in the U.S., Germany, and the Netherlands is rarely used in the 20MHz-6GHz band [41]. The spectrum occupancy in 20MHz-to-3GHz was found to be 32% for indoor scenarios (in the case of outdoor, however, almost 100%, of this range is utilised), and very low in 3-to-6GHz [62], [136]. Such results highlight the fact that the LSA framework, can allow co-existence of one/multiple MNOs with incumbent systems to dynamically exploit unutilised licensed spectrum in a shared manner [137]. In fact, this framework as a promising type of licensed sharing schemes [138], has attracted considerable attention. In this regard, in this section, the LSA framework and its deployment requirements, technical and business challenges, as well the relevant literature are comprehensively studied.

A. Overview of LSA Framework

As discussed in Section III, the concept of ASA initially was proposed to make use of the IMT bands in 2.3GHz and

3.8GHz [21] (in Europe) plausible for mobile cellular network on a monetary basis without the control of NRA and no guaranteed protection for the ASA users (i.e., cellular systems). Firstly, the concept was proposed by QUALCOMM [139], and developed further by CEPT, taking into account more comprehensive regulatory aspects (i.e., the level of authorisation), in order to form a more robust sharing regime, known as LSA. In the LSA framework, a non-mobile wireless service provider, which could be a governmental/commercial incumbent, agrees to share part of its exclusive band with one or multiple MNOs, referred to as LSA licensees [48]. The framework was introduced with the aim of offering promising opportunities for the capacity and bandwidth expansion in cellular systems [137]. The initial target bands of LSA comprise the sub-6GHz such as 2.3-2.4GHz (in Europe), and 3.5GHz (in the U.S.) that are already owned and used by military and also Program Making and Special Events (PMSE) [2], [52], [141]. LSA licensees and incumbents provide different services, originally operate on different bands and are subject to different regulatory constraints.

LSA framework is categorised under vertical sharing (see Fig. 1) schemes where users are labelled as PU or SU. The definition of primary and secondary services is provided by the ITU-R regulations and indicates that the secondary service providers are not protected from the probable interference that is incurred by the primary service providers. Although the LSA framework is defined as being binary in nature, it is expected that it can provide a reasonable level of access when/where the shared spectrum is required by the LSA licensees [142]. In contrast to opportunistic shared access techniques such as TVWS, Wi-Fi, etc., in LSA, an exclusive and guaranteed access to spectrum for the mobile operators are agreed in a particular geographic area/time. Hence, QoS can be guaranteed for services operating in the shared LSA bands. However, based on the predefined rules in LSA, incumbent systems will have the right to ask for evacuation of the shared bands.

The most considerable difference between the LSA framework and inter-operator spectrum sharing is the traffic usage pattern. Since in the latter, the traffic load of MNOs dynamically varies, therefore, the availability of empty bands potentially changes in a dynamic manner. In contrast, in LSA, depending on the type of incumbent, the bands usually become available for a rather longer time intervals (typically several months/years) or wider geographical areas. Thus, the MNOs will be able to develop a clear business plan for the shared bands resulting in predictable revenue [137]. As an example, military (as a governmental incumbent) can introduce specific exclusion zones (temporal and/or geographical restriction) on a long-term basis. However, 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 sharing players.

B. Deployment Requirements

Similarly to inter-operator sharing schemes, in LSA also, the sharing process involves adoption of coordination techniques to protect sharing players from interference. However, in the case of LSA, more accurate and strict interference management policies are required, compared to the case of inter-operator sharing. This is mainly as a result of severe sensitivity/vulnerability of the incumbents, such as radar systems to the interference incurred 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). It can be setup and managed by the incumbents or the respective NRA. The database stores the information regarding the shared spectrum availability/usage of the incumbent's network. 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 [143]. 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 [52], [137].

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. The reference system architecture of LSA framework is illustrated in Fig. 8.

C. Challenges of Deployment in Mobile Cellular Networks

As discussed earlier, the emerging deployment of LSA framework in mobile cellular systems will bring benefits which mitigates the capacity related concerns. However, the advantages will be in conjunction with some challenges which have to be investigated prior to the deployment [144]. Some of them are investigated below.

- *Traffic steering and load balancing:* As discussed earlier in this section, 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 UE over its own exclusive bands. The band evacuation phase becomes concerning if BSs do not have the reconfiguration capability (at the time being, BSs are capable of operating only in a single band at a time, i.e., either LSA band or typical exclusive bands). Therefore, any time the bands are requested by the incumbent, the BS should stop operating and a shutdown process must be carried out. The MNO needs to perform traffic steering and handover and serve the UEs through adjacent BSs, which are operating in typical exclusive bands [145]. In the case that the target BSs are heavily loaded and are not able to accommodate the UE right away, leading to increased queuing or even connection dropping. Thus, this problem needs to be further considered when the LSA bands are dynamically reclaimed

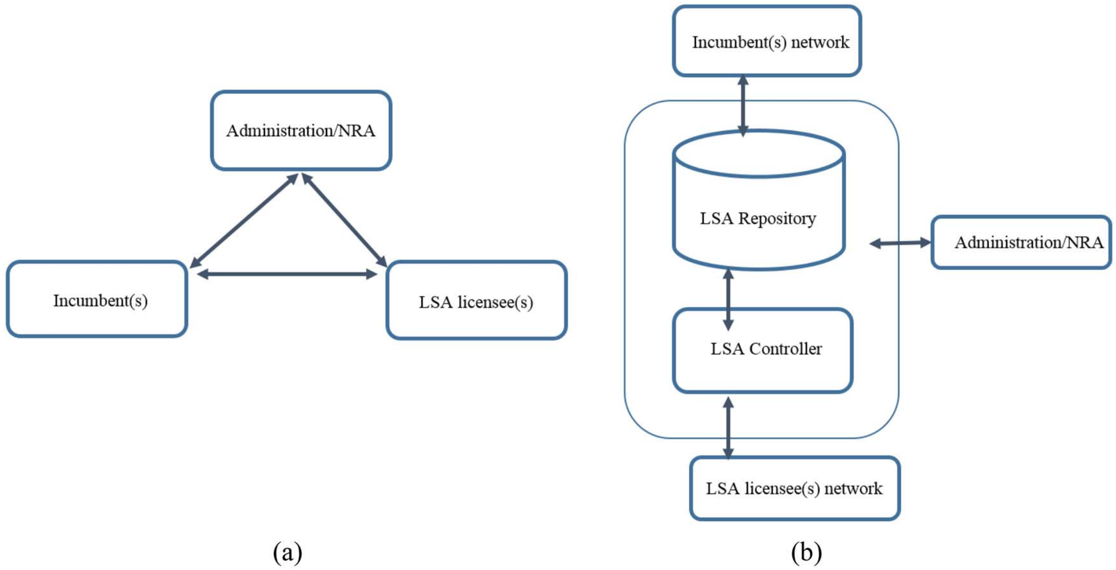

Fig. 8. High level LSA reference architecture; a) administrative, and b) functional implementation [137].

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 [52]. According to [145], 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 [146].

- *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 (e.g., LSA bands in 2.4GHz and LTE bands in 2.6GHz), there is a need that both BS and the UEs to be capable of supporting non-contiguous CA [51].
- *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 [52], [137], [141].
- *Signalling overhead:* The other concerning issue is the additional signalling introduced to the network of both sharing players. In this regard, an efficient interface between the LSA controller and the MNOs network, along with the appropriate network 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, 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 infrastructure (i.e., BSs' site) and connect with their CN node through an entity that has a direct connection to either the SG or the MME over the S1 interface connection. From the mobile cellular network perspective, according to [51], under current LTE specifications from Rel. 11 onwards, the required signalling for the implementation of LSA is supported in MAC and PHY on both UE and BS sides. Besides, in some works such as [147] a "LSA management unit" is suggested to be deployed, to have control over the entire network of an MNO for faster decision making procedure. It collects some information such as traffic status, location, transmit power of a cell and also the direction, height and angle of antenna (i.e., the BS) which also helps interference mitigation between incumbent and MNO, and therefore to have better utilisation of the LSA bands.
- *Dynamic spectrum opportunity detection:* Spectrum sensing can be added as a complementary method to make the database (LSA repository) more accurate and dynamic by taking advantage of 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 for efficient resource management [148].
- *Inter-RAT interference:* As a practical example of such case, cellular systems operating on LSA bands, i.e., 2.4GHz, alongside with Wi-Fi (in the adjacent bands) can 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 [149], 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.

D. Business and Regulatory Aspects of LSA

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 [48], the tasks of different management units may also be defined in different trends.

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. A number of business models have nonetheless been proposed and discussed in technological, regulatory and business aspects [48], [50], [101], [138], [142]. 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. 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.

E. SOTA LSA Experimental Trials and Research Investigations for Enhancements

The performance of the reference LSA framework, in mobile cellular systems, has been evaluated through some trials. Moreover, an ongoing research is being carried out to investigate whether different coordination techniques (some of them studied in Section IV) can enhance current LSA framework performance. A discussion of representative SOTA approaches is provided below.

1) LSA Trial Demonstrations: In [145] and [150], the results from trials of the reference LSA framework (i.e., the conventional LSA architecture) in time-division LTE specifications are presented and discussed. The PMSE as an incumbent in 2.3-2.4GHz bands is considered. Based on the trial results, it is stated that the implementation of LSA is plausible with the minimum required network components (i.e., LSA repository and LSA controller). Besides, the time duration that is required for the band evacuation process, as well as the handover procedure to serve the user on the exclusive bands, is estimated to be acceptable to preserve users' QoS. However, the results imply that further optimisation is required to reduce the duration of sharing procedure (i.e., band evacuation, switching-off the respective BS which is operating in LSA bands, and in parallel real-time traffic steering) to serve the users in the typical cellular bands. In [151], the authors present the most recent trial results incorporating Self Organising Network (SON) techniques into the LSA controller. A significant reduction of delay, 85%, is reported (from 21s to 3s) in the band evacuation phase.

2) LTE Power Adaptation and Beam-Steering/Tilting When Co-Existing With LSA Incumbent: As mentioned earlier in this section, the interference avoidance goes more challenging when the location of the LSA incumbent varies by time (e.g., in the case of PMSE services using 2.3-2.4GHz bands for wireless cameras in three different locations, on top of the building or mounted on helicopters). As in this case, the LTE BS shutdown procedure in a short time scale is not an optimal solution (almost impossible), in [141], the authors apply power adaptation and beam steering techniques instead.

Similarly, in [146] and [152], the study of applying smart antennas (down tilt) techniques in LTE BSs, is carried out. In this respect, by dynamic adjustment of the radiation pattern of the antenna, the LSA exclusion zones (which are typically pre-defined conservatively wide) can adaptively vary, result in the availability of shared spectrum in a wider area. The more interesting benefit emerges when there is no need for the LTE BS (which operates in shared LSA bands) to be shutting down during the band evacuation phase. The evaluation results in [141], show 10% improvement in terms of average LTE user throughput while using LSA shared bands.

3) Enhanced LSA; Applying REM Techniques: Some incumbent systems, such as *radar*, transmit on high powers up to the ranges of megawatts. Also, their radiation pattern varies in time and space. Besides, radar receivers are highly sensitive and consider the noise as the interference from the mobile cellular system side [71]. In this regard, the exclusion zones are defined up to the tens of kilometres (to protect incumbent users), which involve a rather wide area and limit the effectiveness of LSA framework. On the other hand, in the current architecture of LSA, the LSA repository/database is not capable of monitoring the spectrum usage patterns in a real-time basis (database related issues discussed in Section IV). Thus, applying complementary techniques such as sensing of the radio environment to determine whether a particular frequency is in use, and to estimate the propagation environment accurately, can provide more assurance that any subsequent transmission won't interfere with existing systems. Given above, REM technique, as a potential solution is being investigated.

REM is known as an enhanced cognitive technique cable of collecting, processing and storing dynamic varying multi-domain environmental information. In the context of spectrum sharing, it is referred to the spectrum situational awareness with the aid of transmission observations which facilitates characterisation of CRNs to identify how particular bands are being used, and estimation of spectrum occupancy in particular area [153]. REM can be considered as an enhanced form of geolocation database (which is typically applied to store static information of spectrum availabilities) and is capable of covering geolocated radio measurements information comprising characteristics of spectrum use, geographical terrain models, propagation pattern of transmitted signals, interference levels, activities of neighbouring nodes/devices, and regulations, etc. Based on this information, a map of CRN is constructed, which facilitates monitoring of the network [154]. REM information is stored in an entity such as a database and is updated with the observations which are frequently reported by measurement capable devices such as UEs or dedicated sensors (which are setup in the fixed positions). In fact, REM exploits spectrum sensing in conjunction with geolocation database-based techniques for the map construction [155].

REM first proposed in [42] to support for cognitive functionalities (such as situation awareness, network planning, and decision making) in wireless local area networks and also has been developed in several EU-funded projects, such as FARAMIR [155], and QoSMOS [156] for LTE in TVWSs. Recently, the implementation of REM in the *intra-operator* scenarios for the purpose of RRM (such as in-band coverage/capacity improvement, self-configuration and self-optimisation of femto cells, vertical handovers optimisation, intra-system handovers optimisation) has been investigated in ETSI standards [157].

In the context of spectrum sharing, a system model has been proposed by ADEL project [148], with the aim of enhancement in the current LSA framework to perform resource allocation tasks more dynamically. This has been accomplished by adding new functionality to the LSA architecture, which is applying sensing technique that helps the LSA repository to have real-time control over the network. The information is provided by sensing, characterises a map of the current state of radio environment which assists the database (i.e., the LSA repository) for a more efficient spectrum sharing scheme. The performance has not been evaluated yet and only the probable system requirements for the deployment are being investigated in this step. However, this model has been previously proposed in [158], and also now is being tested under the leadership of "RED Technologies".

In the context of REM, an interference mitigation scheme using *spatial interpolation* techniques in the uplink of LTE networks operating on LSA bands, is investigated in [9]. In the uplink, due to the movement of UEs, and therefore the different distances to the BS, the transmission power of UE changes. Thus, the level of interference is not fixed and varies over time and spatial dimensions. This becomes challenging especially when the number of UEs is large and the calculation of the aggregate interference to compare with the interference threshold, defined by the incumbent, is not simply feasible. In this work, the deployment of the wireless sensor nodes in the network and the respective information collection (i.e., received power at particular locations) are considered in order to facilitate the estimation of interference. The results show that this technique provides improved performance in terms of accuracy of the information for interference mitigation compared to the existing approaches in detection theory [9], [51]. However, in such techniques, there is a trade-off between the number of sensor nodes in the network and interference detection.

F. Summary

Applying LSA in 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 assure that the LTE users do not impose harmful interference to the incumbents. Therefore, any implementation of LSA requires extensive experimental performance evaluations in advance. Comprehensive investigations need to be performed in order to determine the achieved gain, while considering the costs of deployment (e.g., additional required components). In [159], a four-phase program is introduced to provide a testing environment (which resembles the actual incumbent systems) to evaluate the performance of new spectrum sharing schemes before the real deployment. Four units are introduced in this testbed to perform the performance evaluation. However, the cost of deployment of such a testbed is estimated to be huge. Hence, a radio frequency virtual test and evaluation environment is introduced in [160], through which operating networks can be simulated as an individually software based model. 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. A summary of SOTA LSA approaches is presented in TABLE V.

The deployment of LSA is in its initial steps. Almost all of the available results in the literature are based on experimental/trial deployments of LSA, while less/no practical implementation has been launched yet. The future of LSA requires enhancements for more dynamic sharing schemes that enable the systems to convert exclusion zones into more coordination zones in a dynamic manner. In this respect, it is expected that the deployment of enhanced REM will have considerable impacts on the performance of current LSA framework.

VII. Lessons Learned and Further Work

In the previous sections, a comprehensive survey of various spectrum sharing paradigms under different deployment scenarios, their benefits as well as potential shortcomings were presented. We studied that by the aid of various spectrum sharing schemes, more or less some additional capacity can be achieved for the MNOs. However, in the context of future mobile cellular systems (namely 5G is considered in this work), there will be much higher expectation of spectrum sharing gains compared to the currently available approaches. The future cellular system is expected to meet the following requirements (some of them which are related to the scope of this work are summarised below) [161], [162].

- Expected 1000-times higher mobile traffic volume comprising MBB, Device-to-Device communications, and MTC for ubiquitous connectivity, which requires cellular systems to support/provide capacity in the order of terabytes/month per subscriber.
- The support of 10-100 times of higher typical end-user data rates, i.e., 10Gb/s for low mobility and 1Gb/s for high mobility (which means wider bandwidth and higher range frequencies will be required).

TABLE V
SUMMARY OF SOTA APPROACHES ON LSA

Project/Paper	Incorporated technique	Aim	Impacts
LSA trial demonstration [151]	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 [150]) to 3s, and a 18% capacity improvement [163].
"Optimisation of Authorised/Licensed Shared access" [141]	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" [158], "ADEL" [148]	Radio Environment mapping	More dynamic and accurate spectrum opportunity detection.	Project ongoing.

- To improve coverage of LTE (more than 20dB), in specific scenarios, implying preference for low (sub-6GHz) frequency ranges, rather than mmWave bands.
- The support of 5 times reduced End-to-End latency (15ms in current LTE), hence, in the development of efficient spectrum sharing mechanisms, this factor should be considered.
- The support for 10-times more energy saving (10% of today's consumption), and therefore longer battery life for low-power devices; Hence, it might be necessary to reduce the burden of sensing from UEs to the enhanced cognitive based sensing techniques for the idle spectrum opportunity identification procedure.

Given above, from the spectrum perspective, 5G systems 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 inter-operator spectrum sharing will enable 5G systems to have greater flexibility for the capacity provisioning, on a condition that coordination between sharing parties 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 [117], [126], [127], [164].

A simple comparison between the achieved gains of the different spectrum sharing approaches summarised in TABLE IV and V, with 5G requirements discussed in this section, reveals that spectrum sharing requires further enhancements in order to achieve higher gain for the real-world deployments. In this context, the enhancements/developments of the following techniques as potential solutions (which are likely to be part of the next evolutionary steps of the future of inter-operator spectrum sharing and LSA) are recommended in this article, and outlined in the following sub-sections.

A. Inter-Operator ICIC

Coordinated Multi-Point (CoMP) as an advanced ICIC 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 [165]. 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 [75]. 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 [75].

B. Enhanced Inter-Operator Coordinated Beamforming Techniques

In Section V, the deployment of beamforming as a potential coordination technique, when MNOs simultaneously operate on shared spectrum in the same area, was studied in detail. However, there are important open issues that have to 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 [133], [166], through an interface with reasonable capacity/speed. Similarly 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.

C. Enhanced REM

The deployment of REM (which discussed in Section VI) is expected to be noticeably beneficial as a hybrid coordination technique in spectrum sharing [155]. However, the practical deployment of REM in cellular systems/LSA architecture faces several challenges, and in this respect, many questions yet to be answered, which necessitates broader research in this field. For instance, to update the database in a dynamic manner excess signalling load will be imposed on the network, and therefore ideal backhauling, as an interface, between 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 is not known yet. It has not been 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 propagation measurement for indoor small cells, energy consumption of UEs (in the case that UEs participate in measurements), all will require comprehensive investigations [154]. Nonetheless, despite all the aforementioned challenges, 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 [158], which indicates the important role of this technique in the future cellular systems.

D. Enhanced RAN Sharing Schemes

The potential impact of RAN sharing to reduce the costs of network deployment discussed in detail. In the context of spectrum sharing, MOCN as one type of RAN sharing (which discussed earlier in this paper) can help facilitate inter-operator spectrum sharing and with reduced over-the-air/wired signalling (of coordination between operators). For the practical deployment of MOCN broad investigations and research are being carried out and different techniques such as virtualisation of BSs and spectrum are being explored to simplify the management of shared RAN. However, this technique is on its early stage and faces considerable challenges mainly the depth/level of virtualisation in the RAN and potential impact on RRM functions whilst preserving the balance fairness and system throughput during the resource allocation procedure in order to avoid performance degradation of the system [167], [168]. EU project, SESAME, is an example of recent initiatives focused on addressing the RAN sharing challenges mentioned above [169].

E. Enhanced Spectrum-Sensing Techniques

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, in Section IV. However, in the context of licensed spectrum sharing, sensing techniques will play an important role as complementary trends in conjunction with other techniques. Thus, enhanced sensing techniques will be required that can capture spectrum availabilities across the network in a more reliable manner. Some factors such as reduced energy consumption for UEs while performing sensing, reduced sensing time duration, will be the representative targets of spectrum sharing schemes.

F. LSA Framework Enhancement

LSA is expected to be one of the key tools for capacity augmentation in 5G systems. However, the existing functionality of LSA framework (as proposed by ETSI) is static in nature (with rather a wide temporal/geographical exclusion zones) to ensure strict incumbent interference protection. Allocation of static LSA-spectrum in 5G may lead to underutilisation of spectrum, as the MNOs may not utilise the bands in all the areas or times. Moreover, 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 systems, small cells can utilise higher frequency ranges (e.g., mmWave), and LSA bands are expected to be in demand for outdoor use. 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-spectrum opportunity detection.

VIII. Conclusion

In this article, we provided a comprehensive survey of licensed spectrum sharing mechanisms for cellular systems. The main objectives of this work were to clarify the importance of spectrum sharing in future cellular systems and also to identify the gaps and therefore the required steps towards the design and implementation of the most efficient sharing algorithms to meet the various system requirements.

Thus, we studied various existing sharing scenarios with different network topologies and also investigated their features, challenges and probable use cases. It can be concluded that, although the progress seems promising, a lack of efficient and cost-effective sharing schemes can still be observed. Of course, the shared use of spectrum introduces some complex issues such as interference to the systems that are currently operating in exclusive bands, but they would not seriously impede the deployment of spectrum sharing if they could 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 interference management, multi-band resource scheduling, and accurate sensing with reduced signalling overhead to get the most benefit of a sharing scheme. Moreover, the enhanced multi-band scheduling algorithms should be capable of responding to the on-demand/highly dynamic resource request as fast as possible to reduce the latency. When designing a sharing algorithm, attention needs to be paid to the fact that a practicality of dynamic sharing scheme with reduced technical complexity and burden of additional investments/costs to the sharing parties is preferable. It also should be noted that this survey was performed based on the current architecture of the cellular systems. Therefore, if new types of services, such as emerging MTC, are expected to be accommodated inside the cellular systems, enhanced regulatory regimes, as well as new system requirements, functions, interfaces will have to be taken into account.

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