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5G Technology: Towards Dynamic Spectrum Sharing Using Cognitive Radio Networks

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ABSTRACT The explosive popularity of small-cell and Internet of Everything devices has tremendously increased traffic loads. This increase has revolutionised the current network into 5G technology, which demands increased capacity, high data rate and ultra-low latency. Two of the research focus areas for meeting these demands are exploring the spectrum resource and maximising the utilisation of its bands. However, the scarcity of the spectrum resource creates a serious challenge in achieving an efficient management scheme. This work aims to conduct an in-depth survey on recent spectrum sharing (SS) technologies towards 5G development and recent 5G-enabling technologies. SS techniques are classified, and SS surveys and related studies on SS techniques relevant to 5G networks are reviewed. The surveys and studies are categorised into one of the main SS techniques on the basis of network architecture, spectrum allocation behaviour and spectrum access method. Moreover, a detailed survey on cognitive radio (CR) technology in SS related to 5G implementation is performed. For a complete survey, discussions are conducted on the issues and challenges in the current implementation of SS and CR, and the means to support efficient 5G advancement are provided.

INDEX TERMS 5G, new radio, spectrum sharing, spectrum efficiency, cognitive radio, enabling technologies.

I. INTRODUCTION

5G is the next-generation mobile communication technology designed to provide greater capacity and higher data speeds than the previous generation Long Term Evolution (LTE). 5G technology, which is expected to be realised by 2020 [1], [2], promises ultra-low latency and ultra-high reliability, thus enabling innovative services across different industry sectors [3]. 5G standards are currently under development and will include the evolution of existing LTE and 5G New Radio (NR) technologies. Several 5G application services have been identified according to International Telecommunication Union (ITU) standards. These services include enhanced Mobile Broadband (eMBB), massive Machine Type Communication (mMTC), Ultra-Reliable Low-Latency Communication (URLLC) and fixed fibre-like wireless access. Each user is expected to experience a minimum of 100 Mbps data rate with a peak data rate of 20 Gbps [2], [3]. For data rates higher than 100 Mbps, Fixed Wireless Access (FWA) or fibre-like wireless can be used. This broadband wireless access is beneficial for residential customers and enterprises using pre-5G or 5G access technologies, including full-dimensional Multiple-Input Multiple-Output (FD-MIMO), massive MIMO and millimeter wave (mmWave) radio access technologies [3], [4]. In ITU's radiocommunication International Mobile Telecommunications (IMT) 2020 vision, at least 800 MHz of contiguous spectrum per 5G network is required for very-high-capacity 5G networks, such as hotspot and FWA connectivity.

In recent years, applications, such as virtual reality, augmented reality and cloud-based services, have emerged and become an integral part of the new generation's lifestyle. By 2030, the vision of connecting 50 billion devices is

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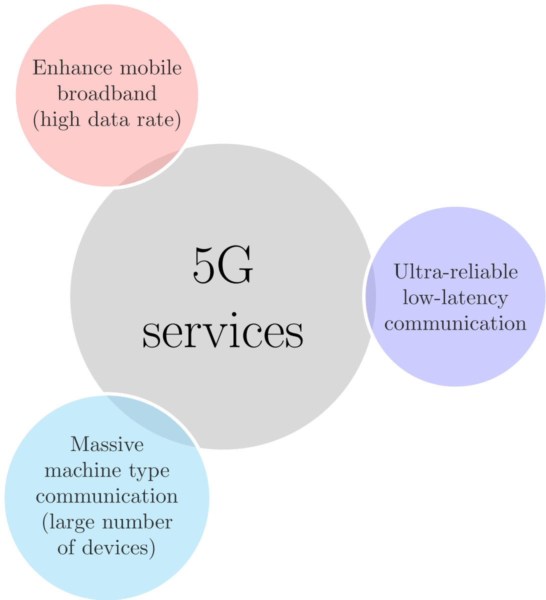

FIGURE 1. 5G application services.

expected to be realised as part of the Internet of Things (IoT) evolution. Sensors, actuators, electronic appliances, street lighting and other devices will be wirelessly connected to the Internet and one another via device-to-device (D2D) communication, which is also known as massive Machine Type Communication (mMTC). Other advancements will demand URLLC; these advancements include connected and autonomous cars, aerial vehicles, remote control of robots in extreme hazardous conditions, industry automation as part of Industry Revolution 4.0, remote surgery and smart grid applications. With the realisation of 5G technology, ultra-fast, ultra-reliable and ultra-low latency application services can be achieved, as compactly illustrated in Figure 1.

5G will benefit numerous industry sectors and accelerate many applications, such as IoT and Mobile Edge Computing (MEC). According to a study by Rimal *et al.* [5], highly localised services are required in Radio Access Networks (RANs) that is in close proximity to mobile subscribers. This requirement has led to the emergence of the MEC concept, in which cloud services are delivered directly from the network edge. Authors have also discussed potential service scenarios for MEC, such as edge video orchestration and distributed caching, backhaul optimisation, vehicle-to-vehicle/roadside communication and IoT services. Other have identified the design challenges of MEC-enabled networks, namely, network integration and coordination, distributed resource management, coexistence of human-to-human and MEC traffic, cloud and cloudlet interoperability, reliability and mobility. Furthermore, the possibility of integrating Fiber Wireless (FiWi) access networks to offer MEC capabilities has been explained with different design scenarios from the architectural perspective. The scenarios are as follows: (1) MEC over FiWi networks, (2) MEC over Ethernet-based FiWi networks, (3) MEC over 4G LTE-based FiWi networks and (4) coexistence of MEC and centralised-RAN (C-RAN) in FiWi LTE-A Heterogeneous Networks (HetNets). In the same study, the authors provided a performance analysis of MEC over Ethernet-based FiWi in terms of delay, response time, efficiency and battery life to demonstrate the feasibility of MEC over FiWi. The results showed the significant benefits of MEC over FiWi networks, with efficient human-to-human/MEC coexistence without network performance degradation.

Numerous researchers have exerted a substantial amount of work to enable applications, such as MEC. An overview of the current status of 5G industry standards, architecture, spectrum allocation, use cases, relevant scenarios and state of the art system advances was presented in [3], [6]–[11]. [12] and [13] studied the opportunities and challenges faced by existing solutions in implementing mmWave for 5G, including the characteristics of and standards in enabling mmWave and related applications (small cell (SC) access, cellular access and wireless backhaul). The authors presented a thorough discussion of the directions of mmWave in the future mainly in terms of physical layer technology (MIMO at mmWave and full-duplex (FD)), software-defined architecture, control mechanisms, network state measurement and HetNet. A comprehensive analysis of various types of 5G potential waveforms was recently performed by Samal *et al.* [14]. They discussed issues related to single-carrier modulation schemes suitable for mmWave in 5G wireless communication systems and enumerated the limitations of Orthogonal Frequency-Division Multiplexing (OFDM), Orthogonal Frequency-Division Multiple Access (OFDMA) and single-carrier frequency-division multiple access (SC-FDMA) spectrum access schemes.

A survey of the current state-of-the-art research in 5G-IoT was presented by Lie *et al.* [15], with focus on the key enabling technologies, the main research trends and the challenges. Despite extensive research effort on 5G-IoT, the technical challenges identified by the authors involved the 5G-IoT architecture, namely, scalability and network management (NM), interoperability and heterogeneity, security assurance and privacy concerns. The challenges in wireless Software Defined Network (SDN) for 5G data networking, Network Function Virtualisation (NFV), D2D communication with efficient spectral resource and interference management, large-scale (with limited resource) and heterogeneous environment of IoT application deployment and multiple access FD transmission remain to be addressed for the successful commencement of 5G-IoT.

Considering recent research, this study is expected to provide an overview of the most recent advancements in 5G-enabling technologies. Our latest study has shown that one of the most urgent issues in future implementation is the scarcity of the radio spectrum [16]. Currently, wireless connectivity is prevalent worldwide and makes full use of the available spectrum band. Unlicensed bands are often congested due to overuse [17], and licensed bands are always underutilised. The Federal Communication Commission indicated that only 5.2% of bands below 3 GHz are utilised at a given time or location. This situation presents an opportunity to solve spectrum scarcity by using the spectrum sharing (SS) concept within a band to maximise spectrum utilisation. An in-depth survey of previous reviews on SS by other authors is conducted, followed by a discussion of the most recent methods in SS. CR is one of the methods with promising implementation. The analysis performed in this study highlights the issues and challenges in current CR implementation to provide insights into potential research directions.

The main contributions of this study are summarised as follows:

- A complete list of the most important 5G-enabling technologies and a brief overview of each technology are provided.
- Different SS techniques are classified.
- Related SS surveys conducted from 2014 to 2019 are reviewed. The focus and contributions of each study are summarised and presented in a table.
- Related studies on SS techniques relevant to 5G networks are reviewed. The studies are categorised into network architecture, spectrum allocation behaviour and spectrum access method, which is also one of the main SS techniques. Related SS works focusing on energy-efficient (EE) improvements are also discussed. The related works are summarised, compiled and presented in a table.
- CR technology in SS and other applications related to 5G implementation are reviewed. CR in SS can be considered a potential technology that can propel 5G networks into the future.
- The issues and challenges in the current implementation of SS and the improvement of current methods to support 5G advancement and efficiency are discussed.

The rest of this paper is organised as follows. Section 2 discusses current 5G-enabling technologies in literature. Section 3 focuses on SS methods, including surveys and recent works, and summarises them in a tabular form. Section 4 discusses the evolution of CR technology related to SS and 5G applications. Section 5 discusses the issues, challenges and future research directions of SS and CR. Section 6 concludes the work. Table 1 lists the acronyms and notations used in the paper.

II. 5G ENABLING TECHNOLOGIES

The deployment of 5G systems has sparked countless academic studies and greatly benefited society. A few important enablers empower 5G technology in communication networks, as illustrated in Figure 2. Each enabler has its own features, and the combinations of enablers define 5G technology.

TABLE 1. Definitions of acronyms and notations.

Acronym	Definition
3GPP	Third Generation Partnership Programme
AP	Access Point
BS	Base Station
CBSI	Concurrent Best Response Iterative
CoMP	Coordinated Multipoint
CR	Cognitive Radio
CRN	Cognitive Radio Network
D2D	Device-to-Device
DCR	Dynamic Channel Reservation
DSA	Dynamic Spectrum Access
DSM	Dynamic Spectrum Management
DTO	Dedicated Telecommunication Operator
E-CRN	Enhanced Cognitive Radio Network
EDSS	Energy-Aware Dynamic Spectrum Sharing
EE	Energy-Efficient
eMMB	Enhanced Mobile Broadband
FD-MIMO	Full-Dimensional Multiple-Input Multiple-Output
FD	Full-Duplex
FiWi	Fiber Wireless
FWA	Fixed Wireless Access
HD	Half-Duplex
HetNet	Heterogeneous Network
IoE	Internet of Everything
IoT	Internet of Things
ITU	International Telecommunication Union
LAA	Licensed Assisted Access
LSA	Licensed Shared Access
LTE	Long Term Evolution
M2M	Machine-to-Machine
MAC	Media Access Control
MEC	Mobile Edge Computing
MIMO	Multiple-Input Multiple-Output
ML	Machine Learning
mmWave	Millimeter Wave
mMTC	Massive Machine Type Communication
NE	Nash Equilibrium
NFV	Network Function Virtualisation
NM	Network Management
NOMA	Non-Orthogonal Multiple Access
NR	New Radio
OFDM	Orthogonal Frequency-Division Multiplexing
OFDMA	Orthogonal Frequency-Division Multiple Access
PA	Power Allocation
PIR	Private Information Retrieval
PN	Primary Network
PR	Primary Receiver
PT	Primary Transmitter
PTO	Public Telecommunication Operator
PU	Primary User
QoE	Quality of Experience
QoS	Quality of Service
RAN	Radio Access Network
RSD	Received Signal Power
RSS	Radio Spectrum State
SAPI	Spatial Adaptive Play Iterative
SAS	Spectrum Access System
SC	Small Cell
SC-OFDMA	Single Carrier Frequency-Division Multiple Access
SDN	Software Defined Network
SIC	Successive Interference Cancellation
SINR	Signal-to-Interference-plus-Noise Ratio
SN	Secondary Network
SNAM	Size-Negotiable Auction Mechanism
SNR	Signal-to-Noise Ratio
SON	Self-Organising Network
SS	Spectrum Sharing
SU	Secondary User
TDD	Time Division Duplex
TVWS	Television White Space
UDN	Ultra-Dense Network
URLLC	Ultra-Reliable Low-Latency Communication
VCFG	Virtual Coalition Formation Game
WiFi	Wireless Fidelity

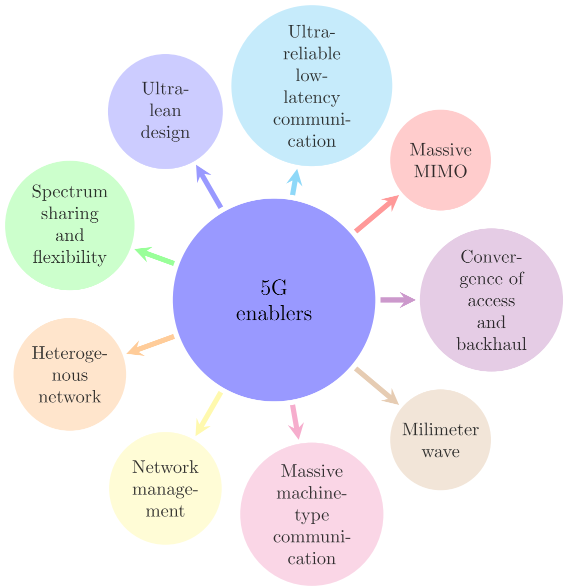

FIGURE 2. Important 5G enablers.

A. HETEROGENEOUS NETWORK

Currently, the emergence of various devices using wireless and IoT technologies is increasing remarkably. Networks that combine different cell types and access technologies are called HetNets. An example of the HetNet architecture is shown in Figure 3. Various types of devices are connected to a femtocell base station (BS) covering multiple small subsets of macro BS. Given that the network is flexible, further research on implementing this network is important to avoid interference and fulfil the Quality of Service (QoS) promise to end users [18]. Therefore, researchers are evaluating the performance of FiWi-enhanced LTE Advanced (LTE-A) HetNets. For example, Beyranvand *et al.* [19] investigated the temporal and spatial probability, delay, maximum aggregate throughput and offloading efficiency of FiWi connectivity. They proposed an algorithm to improve the maximum aggregate throughput performance of FiWi and used the algorithm to enhance LTE-A HetNets as an initial step towards achieving 5G.

A study [21] conducted a comprehensive review of the challenges, technologies and potential use cases of HetNets, with focus on implementing mmWave and massive MIMO in 5G networks. Several challenges that are crucial for effective deployment, such as issues in network planning, traffic management and radio resource management, were reported. The solutions to these issues were presented in several papers. For instance, in [22], the authors improved the call session control function server by adding traffic prediction, bandwidth negotiation and connection admission control to improve traffic management and increase the accuracy of traffic forecasting without sacrificing the prediction accuracy of the system. For ideal large-data streaming in 5G HetNets, an improved version of traditional traffic prediction was proposed by [23]. Another study proposed the development of a linear predictor that uses compressed sensing by adopting support vector classification. The proposed predictor has a simple structure, and its results are promising. The predictor's performance is better than that of the traditional load prediction method. With regard to HetNet network planning, [24] presented a fast handover technique that uses a wireless link signature based on the user location as the handover authentication data. The techniques are time-varying, unpredictable and secured with physical encryption to guarantee a distinct and safe handover.

B. MASSIVE MIMO

Another important 5G enabler is massive MIMO, where data rates are increasing with reduced interference by using the beamforming technique to focus signals on one another [2]. The use of massive MIMO provides low latency and achieves EE communication, which is suitable for 5G development [25]. Massive MIMO is implemented by adopting large-scale and advanced antenna arrays whose width and tilt can be controlled vertically and horizontally. An example of massive MIMO implementation is shown in Figure 4. A uniform planar array, which can be rectangular, hexagonal or circular, is used [26]. Enabling massive MIMO requires regulatory masks to support its statistical nature, and spectrum regulation management must be enhanced to consider time, spatial and direction domains. A recent work addressed Non-Orthogonal Multiple Access (NOMA) in various forms of MIMO-NOMA transmission protocols, designed a cooperative NOMA and identified the relationship between two 5G technologies (NOMA and CR) [27]. The security issues in 5G networks, specifically in the physical layer of massive MIMO, HetNet and mmWave, were also discussed in [27]. A comprehensive survey was conducted by [28], who addressed physical layer technologies, including massive MIMO, new channel model estimation, directional antenna design, beamforming algorithms, Media Access Control (MAC) layer protocols and multiplexing schemes.

Beamforming is a spatial filtering technique that aims to enhance spectral and energy efficiency and increase system security. Hybrid beamforming is a method that combines digital and analogue beamforming. Fully digital beamforming requires a complete radio frequency chain behind each antenna and is impractical for mmWave. Sun *et al.* [29] explored the multi-cell, multi-user, multi-stream communication in mmWave homogeneous networks. The following hybrid beamforming techniques were proposed and compared: (1) leakage-suppressing and signal-maximising precoding, (2) signal-to-leakage-plus-noise-ratio-based precoding, (3) generalised maximum-ratio precoding and (4) feasibility of zero-forcing precoding. The highest spectral efficiency was obtained with the second method. The digital predistortion issue in massive MIMO transmitters for linearising the radio frequency hybrid beamforming array was addressed by [30]. The solution involved the linearisation of the main beam direction for its combined far-field signal,

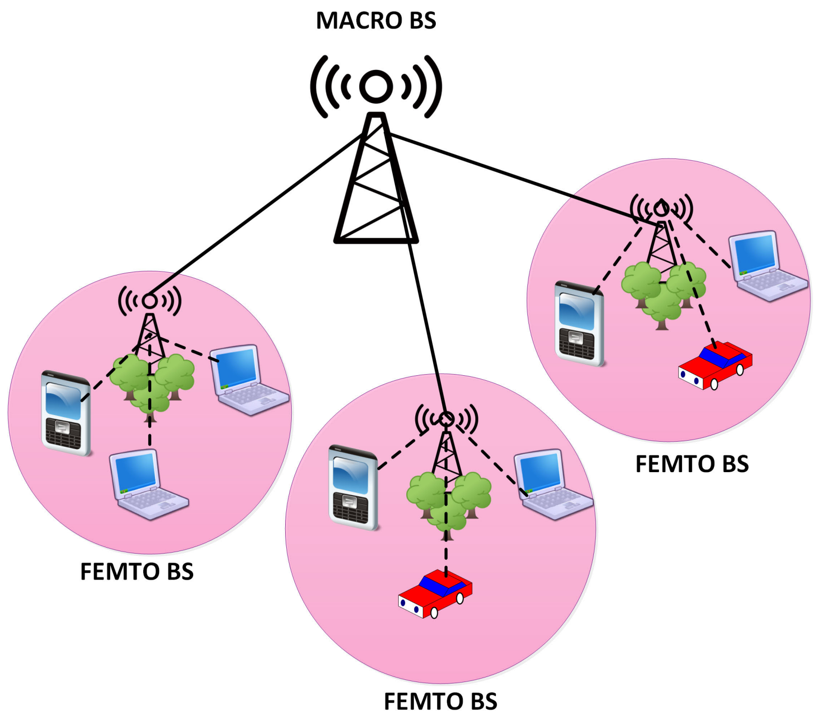

FIGURE 3. Example of HetNet architecture [20].

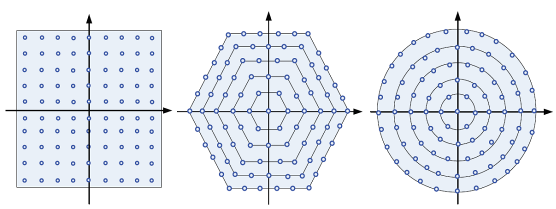

FIGURE 4. Uniform Planar Array configurations, from left to right: rectangular, hexagonal or circular [26].

which can effectively broaden the linear angle range. Hybrid beamforming for single users was applied in mmWave massive MIMO by [31] by using the dual-stage approach based on singular value decomposition and zero-forcing. An issue was identified in the singular value decomposition algorithm, that is, too small or too large channel matrix eigenvalues limit the frequency-selective channels. Adaptive beamforming is a versatile approach of detecting and estimating the signal of interest at the output sensor array via data-adaptive spatial or spatiotemporal and interference cancellation. Research on this method in moving vehicles was conducted by [32] by using a predictor antenna with a 64-element massive MIMO for complex OFDM downlink channels. The obtained accuracy was close to the ideal beamforming gain for non-line-of-sight channels. Further investigation of real-time prediction with realistic time-frame structures in time division duplex (TDD) systems was suggested. Pei *et al.* [33] emulated the line-of-sight channel accurately via pre-faded synthesis and analysed over-the-air 5G cellular communication with adaptive beamforming using a sectored multi-probe anechoic chamber. A recent study by [34] tackled the interference issue by using the adaptive beamforming algorithm to mitigate interference. The algorithm achieves coherence between different beams, and each beam is suitable for a specific terminal. The beamwidth of the main lobe is narrow, and massive MIMO systems can manage the good sectorisation between user equipment without interference. The network capacity and data rate can also be increased.

A highly potential 5G network infrastructure for communication known as cell-free massive MIMO was introduced by [35]. It entails joint signal processing from many distributed access points (APs) and can offer similar QoS to all user equipment despite its low complexity. An illustration of how cell-free and cellular differs is shown in Figure 5. Each AP in cellular massive MIMO is serving an exclusive subset of the users. While cell-free massive MIMO has many distributed APs that are jointly serving the users with the signal encoding/decoding taking place in a CPU. Björnson and Sanguinetti [36] performed the first comparison of cell-free and cellular massive MIMOs. Cell-free massive MIMO was implemented with four levels of receiver cooperation from fully centralised to fully distributed with multi-antenna APs. Cell-free massive MIMO exhibited higher spectral efficiency for all user equipment compared with cellular massive MIMO. Through minimum mean-squared error processing, the received and estimated signals are sent to a central processing unit instead of being preprocessed at APs. Ullah *et al.* [37] proposed

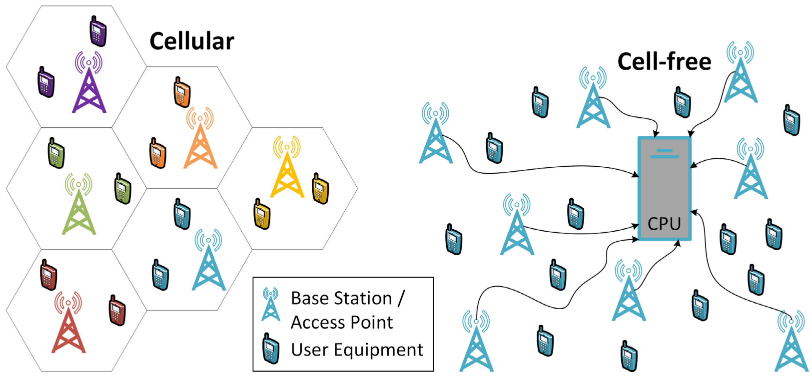

FIGURE 5. Comparison between cellular and cell-free massive MIMO systems [39].

training size optimisation for cell-free massive MIMO systems that is effective when the coherence is low or the number of users is very large. The method can achieve a higher downlink rate than the conventional pilot length method. Zhang *et al.* [38] conducted a comprehensive survey on cell-free massive MIMO systems by exploiting channel hardening and favourable propagation conditions. The exploitation aimed to reduce the transmission energy and inter-cell interference in a centralised or distributed manner. The study showed that cell-free systems provide better coverage than conventional cellular systems and uncoordinated small cells. Chen and Björnson [39] investigated a cell-free massive MIMO network with channel hardening and favourable propagation from a stochastic geometry perspective. They found that hardening can be obtained efficiently by deploying multiple antennas per AP, and having a few multi-antenna APs is better than having many single-antenna APs. Users that are spatially well-separated communicate with different APs subsets and thus exhibit favourable propagation. However, [39] suggested not to rely on both properties when designing and analysing cell-free networks; instead, resource allocation schemes and achievable rate expressions that work well without the two properties should be used.

The 5G network is expected to serve a massive number of users and support instantaneous demand variations at different times and events. Therefore, NOMA has been explored as one of the promising solutions to this problem. An example of work in NOMA is the study of [40], who elaborated on the working principle of the uplink NOMA framework. The data of two users are transmitted simultaneously, and frequency resources and Successive Interference Cancellation (SIC) are used for reliable data transmission. The authors also presented the challenges in implementing a massive number of IoT devices in 5G cellular networks, such as BS and traffic estimation, channel estimation, interference management, power allocation and management of device synchronisation. For NOMA-based multi-user MIMO, [41] presented a joint interference alignment with the power allocation framework to overcome the immense increase in traffic in the data network. The framework utilises the sum rate to provide QoS and guarantee an effective SIC constraint whilst managing the power to reduce interference within a cluster. Furthermore, a NOMA two-way relaying method was developed by [42] by using Karush–Kuhn–Tucker conditions with dual composition techniques. The relay divides single-source data into two parallel parts, which are then transmitted using amplify-and-forward relay. The method can be further expanded to multiple users. The use of NOMA also aims to provide control over the complexity of data processing and signal overhead in 5G networks. In the study of [43], compressed sensing for NOMA for mMTC was presented. The proposed schemes use low coherent spreading, which can improve spectral efficiency and reduce latency by enabling user data detection and joint activity without activity information from the user.

C. ULTRA-LEAN DESIGN

Future 5G technology is expected to enable an ultra-lean design [2], [44] where 'always-on' signals are reduced to a bare minimum to achieve an EE network at a low operational cost, as shown in Figure 6. The implementation of this ultra-lean design can reduce network transmissions without affecting user data delivery [45]. This feature is critical for very dense local areas to reduce the overall interference level for end-user performance at low-to-medium loads and is essential to high-frequency bands where networks are yet to be deployed. Ultra-lean design also needs special attention in terms of backward compatibility for low-frequency bands because a large number of terminals are already deployed. Moreover, the implementation of ultra-lean design in Ultra-Dense Network (UDN) has exhibited significant improvement in enhancing mobility support, increasing throughput and saving energy as experimentally confirmed by [46], who provided future research insights into the deployment of 5G.

D. ULTRA-RELIABLE LOW-LATENCY COMMUNICATION

Another important promise of 5G is the ultra-low latency enabler [2] that can reduce processing delays and transmission time intervals and widen the bandwidth of radio resource blocks in which a specific amount of data is transmitted.

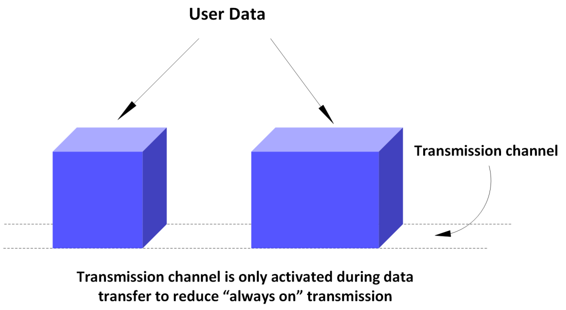

FIGURE 6. Ultra-lean design for 5G data transmission [47].

This feature can also avoid queuing delays at the radio transmitter whilst the direct communication link (i.e. D2D) provides low-latency transmission for devices in close proximity. To achieve this vision, the physical channel structure must be designed for fast decoding at the receiver, and the MAC has to enable immediate access. Collision risks must be minimised by providing dimensioned instant-access resource allocations. Several recent studies performed detailed analyses to achieve this low latency requirement. Lauridsen *et al.* [48] measured the performance of current LTE network implementations and compared it with the initial LTE requirements. They also identified key performance indicators for consideration in designing and standardising 5G technology, including an analysis of critical connected mobility parameters, such as user and control plane latency, handover execution time and coverage. In 2018, Moradi *et al.* [49] proposed a scalable architecture by combining SDN and NFV for a customisable and low-latency 5G core network. The system enabled the creation of custom services for user equipment with low latency and efficient signalling.

E. ENABLERS FOR mMTC

5G technology also needs enablers for mMTC [2] to achieve 'zero-overhead' communication by simplifying the connectivity states of devices and providing channel access with minimal signalling. Maximising the devices' sleep opportunities is also useful in reducing energy consumption. Doing so would lead to long battery life, and devices can operate for years with small batteries. Optical transmission modes are also needed to provide connectivity at low rates. This feature can be attained by providing a 'spectrum-compatible' interface for the best coexistence with legacy radio technology. Jovović *et al.* [50] presented an overview of a next-generation mobile network that integrates all machines and devices via the IoT concept enabled by the deployment of mMTC in 5G network. The main advantages of 5G machine communication is the increased data speed transmission and capacity of up to 1 Gbps, with latency as low as 1 ms. mMTC is also targeted to support emerging services and applications based on the IoT concept. With the implementation of 5G in the future, mMTC will not only promote the IoT concept but will also provide an open opportunity to explore the implementation of the Internet of Everything (IoE).

F. NETWORK MANAGEMENT

Managing a network is one of the crucial issues in any communication technology. Given the multitude of existing services and the additional services to be offered in the new economic sector using 5G technology, intelligent means of managing the network efficiently are urgently needed. Autonomous NMs that have self-awareness, self-configuration, self-optimisation and self-healing properties are necessary for enhanced cost and energy savings. Pulcini *et al.* [51] demonstrated the use of specific procedures based on carrier Ethernet for the reliable management of HetNets dedicated to 5G networks using SDN configured for the implementation of energy saving tasks and QoS control. Self-Organising Network (SON) management in 5G was identified by Moysen and Giupponi [52] as the key driver of improvements in operation, administration and management activities with minimal human intervention. The authors also reviewed the basic concepts and taxonomy of SON, NM and machine learning (ML). SON reduces the installation and management costs of 5G by simplifying operational tasks due to its capability of configuring, optimising and healing itself. The autonomous management vision using SON is expected to be extended to end-to-end networks to satisfy 5G NM requirements.

The planning of ultra-dense wireless networks [53] and the characteristics of typical UDNs that appear in a 5G network were explained by [54]. The study included a comparison with traditional cellular networks based on the definition by ITU. The key issues in applying UDNs in 5G were identified as follows: network architecture and protocol procedure enhancements, interference avoidance and inter-cell coordination, EE and super SON. To address one of these UDN key issues, a survey was conducted on how ML solutions can benefit 5G SON management with an end-to-end perspective [52]. The key improvement of SON is its capability to configure, optimise and heal itself. The evolution of SON in 3GPP was also presented together with detailed implementations of SON on different architectures. The elements that contributed to SON's evolution were discussed thoroughly, including self-configuration, self-optimisation, self-healing, self-coordination, minimisation of drive tests, core networks and SON in virtualised and softwarised 5G architecture. An overview of ML-based NM's relevant literature based on these elements was also presented in a comprehensive manner. Moreover, a high-level classification of different NM problems in managing the SON network was meticulously performed. For each class of problem, the authors identified the ML tools that can be used.

The multiple access and multi-service features envisioned in 5G can be realised by slicing a single physical network into multiple isolated logical networks. Foukas *et al.* [55] presented a review of 5G network slicing in different aspects, namely, virtualisation of radio resources (dedicated or shared resources), granularity of network functions (coarse or fine grained) and service description (human-readable format or set of functions and network components). The challenges that need to be addressed before fully realising the vision of network slicing based on multi-service softwarised 5G mobile network architecture are RAN virtualisation, service composition with fine-grained network functions and end-to-end slice orchestration and management.

The security aspect of 5G wireless communication networks was explored by [56], specifically in HetNets (spatial modelling, mobile association and device connection), massive MIMO systems (low power consumption, TDD operation, artificial noise, antenna correlation, confidential broadcasting and hardware impairments) and mmWave communication (large bandwidth, short range transmission, directionality and large antenna arrays). The authors suggested appropriate ways of safeguarding the said technologies by using physical layer security. Another work conducted a survey of existing authentication and privacy-preserving schemes for 4G and 5G cellular networks [57]. The authors classified the schemes into seven types: (1) handover authentication with privacy, (2) mutual authentication with privacy, (3) radio frequency identification authentication with privacy, (4) deniable authentication with privacy, (5) authentication with mutual anonymity, (6) authentication and key agreement with privacy and (7) three-factor authentication with privacy. The authors also presented a thorough survey of the techniques for threat models (attacks against privacy, integrity, availability and authentication), countermeasures (using cryptography methods, human factors and intrusion detection methods) and security analysis (informal and formal techniques). The opportunities and challenges for security designers in planning future 5G networks were likewise identified [56]. The concept of 5G cellular network was studied comprehensively by [58].

G. CONVERGENCE OF ACCESS AND BACKHAUL

The convergence of access and backhaul [2] can simplify the deployment of wireless connectivity between radio network nodes. Convergence is an alternative to relying on optical fibre alone. It is achieved with the exploration of high-frequency bands, extensive beamforming and low-latency transmission. The combination of these methods can provide high bandwidth that is comparable to an optical link. Convergence can be accomplished with the dynamic split of spectrum resources between access and backhaul for increased efficiency by using the same radio interface for both links. The links can also be used for operational and maintenance systems. Convergence backhaul sharing towards realising 5G was studied by [19] for FiWi-enhanced LTE-A HetNets. Meanwhile, in [59], the authors addressed the convergence of access and virtual backhaul networks. It was implemented with an SDN NFV orchestrator to serve mobile network operator capacity requests automatically by computing and allocating virtual backhaul tenants.

Six major requirements and challenges in preparing 5G backhaul solutions were enumerated by [60]; these six are capacity, availability, cost, long-distance reach requirement, ultra-low latency and UDN. The issues in backhaul access that are foreseen to arise in the 5G environment were discussed by [61]. Backhaul will be used to connect the core network with ultra-dense and heavy traffic cells, thus exposing it to extreme requirements in terms of latency, capacity, energy, cost efficiency and availability. The authors discussed 5G backhaul with evolving and disrupting 5G features, the evolution to a 5G cellular backhaul network in terms of the requirements, the tailored solutions and trade-off between centralised RANs and the fronthaul cost from the perspective of joint backhaul/RAN. The advantages and shortcomings of the backhaul solution, the unsolved challenges and the consolidated 5G backhaul vision were also presented. The enabler and challenges of 5G RAN slicing for vertical spectrum were explained in detail by [62].

With regard to channel assignment in backhaul/access in SC, a comparative observation was performed by [18] to determine the optimal location for backhaul channels by using the maximum received signal power (max-RSP) and the minimum received signal power (min-RSP). The results showed that the min-RSP model outperforms the max-RSP model, implying that backhaul channels are more suitable for use as the cell edge of secondary BS. These channels allow numerous high-density channels in the network to be a base study for future backhaul implementation in 5G networks. Furthermore, a focused study on mobility management for joint access backhaul was conducted by [25], who studied the previous development of backhaul scenarios and listed different approaches in designing joint-access backhaul solutions. The effects of the future backhaul/fronthaul condition on 5G mobility management were also investigated. Intelligence is required in deploying 5G backhaul solutions. Several other aspects, such as adaptive and dynamic adoption and allocation strategies, were also explored by [61] as future research directions.

H. mmWave

For resolving spectrum scarcity issues to realise 5G architecture, mmWave is one of the solutions explored in many studies. mmWave is an ultra-high-frequency band that ranges from 30 GHz to 300 GHz [12]. It provides extremely high data rates, ultra-high capacity, very large bandwidth and very low latency for new services and the economy sector that can benefit from 5G. Authors have discussed the characteristics of mmWave communication, such as wireless channel measurement, directivity and sensitivity to blockage, standardisation of mmWave, challenges and existing solutions in terms of integrated circuits and system design, interference management and spatial reuse, anti-blockage and dynamics due to user mobility and mmWave applications, such as SC access, cellular access and wireless backhaul. Investigations on 5G SS were conducted by [3] for the spectrum below 6 GHz and within the mmWave range. For the application of 5G access fronthaul, the mmWave signal frequency used was 60 GHz which was generated using a dual-wavelength fibre laser [63]. The same authors presented a radio over a fibre system for the transmission of OFDM with 5 GHz bandwidth.

Recently, Samal *et al.* [14] conducted a study on single-carrier modulation schemes that are suitable for mmWave and provided suggestions on using modern signalling schemes for smart grid communication technologies. An entire chapter in the paper of [64] described mmWave in terms of its applications, frequency spectrum, characteristics and standard channel models for 5G networks. They also discussed EE in networks operating at mmWave frequencies, antenna technology, cognitive radio network (CRN) and mmWave technology and the optimisation and projects related to mmWave.

The millimetre band of the unlicensed 59 GHz to 64 GHz is designated for future research on 5G to achieve increased data capacity, throughput and low latency for future dense network traffic. However, using mmWave as the data carrier entails limitations, especially in utilising the 60 GHz band. Generally, mmWave has a short wavelength that varies from 1 mm for 300 GHz to 10 mm for 30 GHz. Given the short wavelength characteristics, mmWave can only travel in less than a kilometre and can be easily blocked by any obstacle along the path. However, this characteristic is useful for object imaging and short-distance networking. For example, the 60 GHz frequency band is used in IEEE 802.11ad as a wireless networking standard [65] for Wireless Fidelity (WiFi) in close areas [66]. As mentioned by [68], mmWave has high oxygen absorption and atmospheric attenuation, which further shorten the coverage and strength of the waves. In addition, mmWave travelling in rain or highly humid conditions experiences signal loss and distortion. For countries with high humidity and heavy rainfall all year long, such as Malaysia [67], implementing mmWave, especially at 60 GHz, is a challenge due to the unsuitable weather [68]. However, the advantages of using mmWave in dense network traffic are too valuable to ignore. Flament [68] addressed the problem of frequency scattering that affects mmWave's throughput performance. The proposed solutions involved using multiple techniques, such as beamforming and leveraging the reflection and refraction of the radio path for D2D communication. Another improvement was proposed by [69]. The proposed solution improves microstrip antenna design with an inserted slot to increase the frequency gain in utilising the 60 GHz band for a point-to-point 5G communication system. Other possibilities are available for implementing the 60 GHz band or utilising other suitable bands for an alternative 5G carrier frequency in unfavourable climate conditions, and they require further exploration.

I. SPECTRUM SHARING AND FLEXIBILITY

SS and flexibility are amongst the most important issues to be addressed in overcoming spectrum scarcity and utilising the spectrum band in 5G technology. SS is a means to optimise spectrum usage by enabling the sharing of the same frequency band amongst multiple users of different priorities without impeding one another. Transmission for NR uplinks and downlinks occurs at new (increased frequency) bands for 5G. LTE/NR uplink SS is one of the 5G enablers because it can co-exist with 5G and share the same low-frequency bands. 5G NR uplink can also exploit the low-frequency bands used by operators for LTE.

TABLE 2. 5G frequency spectrum [4].

Category	Spectrum	Coverage
Low Frequencies	< 2 GHz	• Wide areas • Deep indoor coverage
High Frequencies	2 to 6 GHz	• Focused areas • Relatively large bandwidths • Very high number of connected devices • High speed of concurrent connected devices
Very High Frequencies	> 24 GHz	• Small coverage areas (50 to 200 m) • High traffic demand • Very large bandwidths • Ultra-high capacity • Peak data rates (Gbps) • Very low latency

In terms of spectrum flexibility, a new regulatory framework is needed for a fully flexible radio interface design and the dynamic use of paired and unpaired frequencies [2]. This will allow for smooth adaptation to service requirements, such that the downlink spectrum resource is usable for uplink transmission and vice versa. Future systems are also expected to provide a high degree of spectrum flexibility for high-frequency bands to allow the use of an unlicensed spectrum in boosting the capacity [2] for critical control signalling and mobility handling, preferably in combination with a licensed spectrum.

Spectrum allocation for 5G is categorised into three main bands, namely, low, high and very high, as summarised in Table 2. The spectrum at frequencies below 1 GHz, particularly at 700 MHz [3], [4], enables 5G coverage in wide areas and deep indoor coverage. The spectrum at high frequencies with relatively large bandwidths below 6 GHz (at 3.4 GHz to 3.8 GHz) [3], [4] provides the necessary capacity to support numerous connected devices and ensure high speed for concurrently connected devices. This spectrum delivers the best compromise between capacity and coverage. At very high frequencies above 24 GHz (e.g. 24.25 GHz to 27.5 GHz) with very large bandwidths, the spectrum provides ultra-high capacity and very low latency [3], [4]. The cells at these frequencies have a small coverage (from 50 m to 200 m). The build-out of 5G networks in mmWave bands will initially be focused on areas with high traffic demand or specific locations or premises requiring services with extremely high data rates (in Gbps). This 'pioneer' mmWave band also provides ultra-high capacity for innovative new services, thus enabling new business models and sectors of the economy to benefit from 5G [3], [4]. An overview of the 5G spectrum and its uses is illustrated in Figure 7.

The C-band of the spectrum, which ranges from 3300 MHz to 5000 MHz, is designated as the primary frequency band to introduce 5G in the year 2020. The channel bandwidth provided for 5G must be at least 100 MHz per network to meet the requirements. The implementation is very cost-efficient

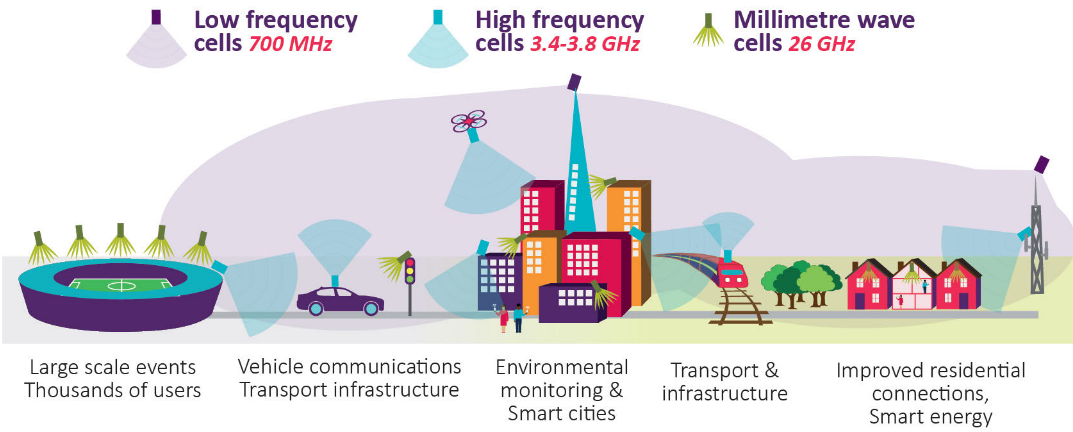

FIGURE 7. Frequency spectrum for 5G and its uses [4].

because the channel capacity can be enhanced without network densification costs. 5G's use of the C-band can be realised by the adoption of massive MIMO for its acceptable complexity and capability to boost peak, average and cell edge throughput. The low frequency used for mobile can also be exploited by combining the 3300 MH to 3800 MHz frequency as one of the 5G features in 3GPP standards through the use of the co-existing LTE/NR uplink.

Amongst all 5G-enabling technologies presented, this work focuses on the potential of fully utilising the limited spectrum band by reviewing recent SS studies dedicated to 5G technology. The reason for such focus is the promising solution for licensed SS. The main advantages are improvements in spectrum utilisation and increment in capacity according to the different types of services required.

III. TOWARDS SPECTRUM SHARING IN 5G NETWORKS

SS has been identified as a potential solution to spectrum scarcity but was initially avoided by network providers/mobile operators in the past due to market competition. However, sharing activities have been observed between mobile operators in recent years mainly due to the limited infrastructure. With SS, capacity demands have increased substantially despite the decrement in average revenue per user [70]. Another advantage of infrastructure sharing is the multitude of costs related to network deployment and maintenance, which leads to low capital expenditure. This is especially true when traffic is low in remote areas. For dynamic and asymmetric traffic, multi-operator SS is beneficial when set in a cooperative manner. However, creating a trustworthy relation between operators is the main issue in the aspects of sharing fairness, data transparency and service quality agreements.

A. CLASSIFICATION OF SPECTRUM SHARING TECHNIQUES

Figure 8 illustrates SS techniques, which can be divided into three main approaches: network architecture, spectrum allocation behaviour and spectrum access method. Network architecture can be either centralised (infrastructure-oriented) or distributed (infrastructure-less) [71]. A comparative analysis of both approaches with different performance evaluation parameters and the associated challenges were presented in [72]. Spectrum allocation behaviour can either be in a cooperative or non-cooperative manner. Dludla *et al.* [73] discussed both behaviours, specifically in Licensed Shared Access (LSA) (non-cooperative) and Television White Space (TVWS) (cooperative). Meanwhile, the spectrum access method is divided into three techniques: (1) dynamic exclusive that consists of a commons model, shared use and exclusive use [17]; (2) open access; and (3) hierarchical model that consists of overlay, underlay and interweave. The commons model and open access are technologies that can enable simultaneous spectrum usage but with limitations, as discussed in [74]. The commons model uses self-regulation, which limits the number of users. The users are in charge of co-managing spectrum usage. This model also has a regulator that assigns and enforces rights but is not responsible for managing the spectrum. The open access model has unrestricted access to the spectrum and can be used by any service or application. No usage rights are enforced, but users must comply with certain rules defined by National Regulatory Authorities (NRAs). Fees may be applied for NRAs to be borne by the users.

The hierarchical model is also known as vertical SS (ITU-R 2014) or primary–secondary sharing [75]. The differences between vertical and horizontal spectrum access were explained by [76] with different sharing scenarios associated with licensed bands from the mobile operators' perspective. The overlay model, which is based on CR technology, is divided into two other models: three-tier and database-assisted models. The database-assisted model has several other methods associated with it, including TVWS, LSA and Spectrum Access System (SAS).

In the underlay and overlay mechanisms of the hierarchical model, secondary users (SUs)) can transmit simultaneously with primary users (PUs) as long as performance degradation does not occur in PUs. However, the underlay model has

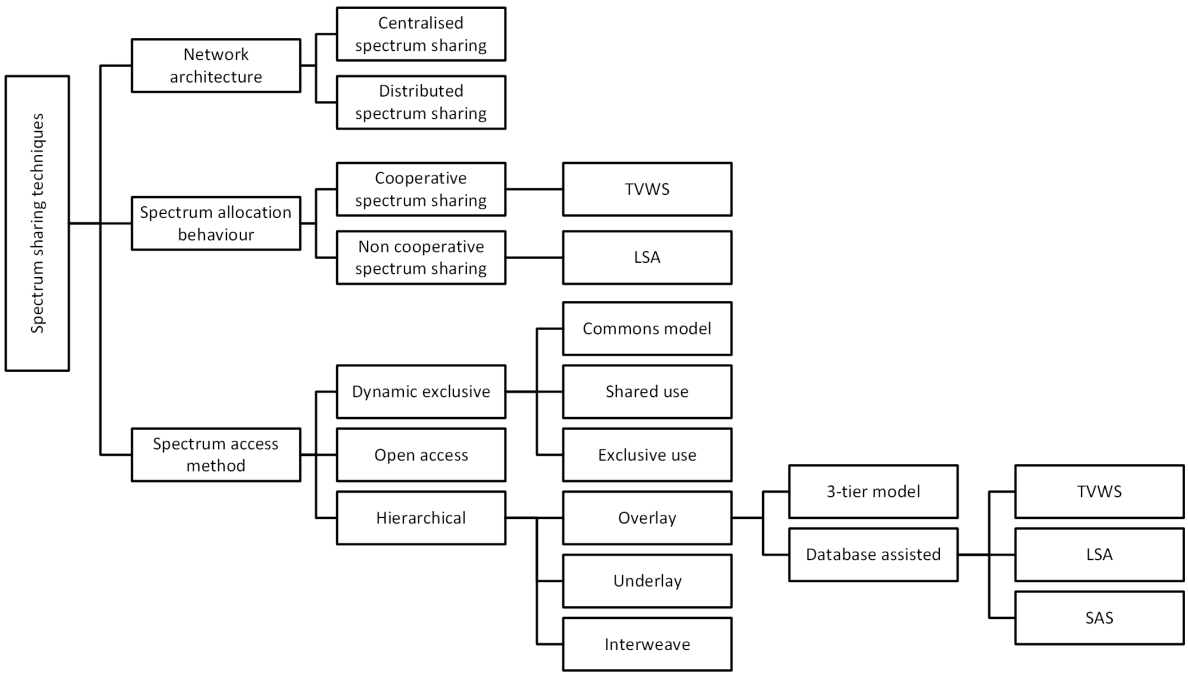

FIGURE 8. **Classification of SS techniques.**

a predefined noise threshold to protect PUs from potential interference, and SUs has to obey it by tuning its power level or must liaise with PU to avoid performance degradation. The interweave mechanism is an opportunistic access model where SU can dynamically access the licensed spectrum on an opportunistic basis whenever PU is not using the spectrum. It can be either in a single domain or in a combination of temporal, frequency and spatial domains [76]. SU transmits over spectrum holes in the licensed band in a specific geographical or time domain. Spectrum holes are the temporary space–time–frequency that is not in use by any licensed or unlicensed user and changes over time [77]. The interweave model also requires information on the user's activity from the spectrum. Spectrum occupancy is periodically monitored and detected by the system. Minimal interference occurs when the system communicates opportunistically over available spectrum holes.

Several SS licenses can be applied for 5G use, such as exclusive use (individual licenses), license-exempt rules (unlicensed or commons), LSA and authorised shared access, citizen broadband radio service with SAS, pluralistic licensing and Licensed Assisted Access (LAA) co-primary shared access. An overview of these license schemes was presented by [70], with legal regulations (in USA, Europe and elsewhere) and trial activities for SS schemes (LSA, LAA and SAS) as well as the characteristics of SS from inter-operator and virtualised network architecture perspective.

B. PREVIOUS SURVEY ON SPECTRUM SHARING

An early survey on the convergence of the current network to a heterogeneous mobile network for 5G communication was conducted by [78] in consideration of the communication of machine-to-machine (M2M) application. The convergence of mobile networks combines device convergence, protocol convergence and service convergence, which are expected to improve QoS. In the future development of M2M technology, the first step is to enhance current OFDMA and MIMO antennas with improvements in end-user device performance. This task can be done by introducing a new network architecture that can support cellular and M2M interconnection. Furthermore, an improved traffic balancing model is also needed for QoS control policies. Interference is one of the challenges in using M2M and cellular in the same spectrum. Therefore, Coordinated Multipoint (CoMP) for interference avoidance and M2M integration for HetNet are suggested for future research.

A critical insight into the challenges in expanding future research on CR in 5G was provided by [79]. The enabling devices are specifically found in the CR terminal and expected to be developed in software-defined devices, and the outcome will allow researchers to study spectrum-related matters more efficiently. The authors specified the important aspects of cognitive terminal challenges, such as adaptive prediction algorithms, seamless connectivity, fast and reliable reconfigurable hardware and dynamic spectrum allocation. For example, with dynamic spectrum allocation, the spectrum can be utilised more efficiently without reducing the transmission quality. However, future research on the implementation of adaptive power and spectrum allocation in MAC is needed. Furthermore, the ability to exchange information is also required to enable high QoS amongst the heterogeneous devices in a 5G network. Problems in security, interference and 5G terminal locations were also critically reviewed in the paper.

The survey on emerging technologies for 5G architecture conducted by [7] focused on massive MIMO, D2D and network architecture. The 5G network architecture was suggested to improve the current network architecture, such as OFDMA, which can still be used for a long time. However, with the current cellular architecture, users inside a building experience high signal penetration loss and reduced data rate and spectral efficiency. Arrays of antennas utilising massive MIMO technology are the enabler for this challenge. SS and shared horizontal and vertical spectrum will be used to obtain increased spectrum capacity for the usage of various devices in the future. To enable SS for the 5G mobile broadband system, two SS techniques were identified: distributed and centralised solutions. The distributed solution is highly efficient when used in a local framework, and the centralised solution is useful for systems with higher granularity than a radio system. This solution divides users on orthogonal resources with incomplete data but has benefits in certainty, control and reliability.

The well-known fundamental challenge in SS is to reliably identify when and where spectrum holes exist. This task is achieved by implementing spectrum sensing and spectrum prediction in the system. The work of [80] verified the fundamentals of predictable and unforeseeable underlying real-world Radio Spectrum State (RSS). The authors provided technical guidance on how to apply the predicted RSS in future wireless communication design. The authors also suggested several applications of spectrum prediction in SS to meet 5G requirements, such as cost-efficient wideband carrier aggregation, dynamic frequency selection and predictive interference mitigation.

A comprehensive survey on the licensed SS mechanism for mobile operators was conducted by [76]. The authors classified the authorisation regimes into three categories, namely, individual authorisation, light licensing and general authorisation. Their focus was on individual authorisation, for which state-of-the-art co-primary shared access (shared use between mobile operators) and licensed/authorised shared access/spectrum access sharing (shared use of license bands between incumbent and mobile operators) were presented. The gaps were analysed, and the requirements needed for efficient sharing algorithms were presented. The paper concluded that the main challenge in SS is the need for efficient and cost-effective sharing schemes. Although other issues exist, such as interference, the authors believed that they do not exert a considerable effect on deployment due to enhanced management approaches. Other challenges in the SS scheme include integrating multiple layer protocols to perform interference management, multi-band resource scheduling and accurate sensing with reduced signalling overhead. The scheduling algorithm for SS must be able to minimise delay by having on-demand and highly dynamic features. However, a trade-off between complexity and practicality must be considered.

In [81], the integration issue of five SS techniques was reviewed together with their potential challenges. The techniques were CR, D2D communication, in-band FD communication, NOMA and LTE on unlicensed spectrum (LTE-U). The authors stated that if the spectrum in the 5G network is to be used exclusively, 76 GHz of spectrum resources are needed, but SS of only 25% of the total spectrum resource is required. The main challenge addressed by CR in the 5G network is the requirement for an EE spectrum sensing scheme because 5G uses ultra-high-frequency bands, thus forcing users to scan a wider bandwidth than that at low-frequency bands. This task appears to be a challenge considering the battery limitation of terminals. A possible workaround for this is to scan a small band instead. However, this workaround imposes a different challenge in which the system must have the cognitive ability to learn from the scan history in order to accurately reduce the frequency range to the correct band. With the implementation of 5G, numerous nodes are expected to be connected to the network. The increased number of nodes in the 5G network is unsuitable for a centralised scheme due to the signalling overhead cost. Another challenge to consider is distributed interference mitigation schemes. Spectrum scarcity increases with increasing nodes.

Although SS is beneficial, the challenges of its adoption must be clearly addressed by operators and competitors to ensure benefits to all parties involved. Furqan *et al.* [70] presented an overview of SS schemes considered for 5G networks and discussed SS techniques, legal regulations and trial activities in detail. Furthermore, a basis of spectrum management for SS was discussed. The study also addressed the challenges of SS in virtualised networks. Amongst the challenges is ensuring service differentiation, which is easy to achieve with exclusive spectrum access. However, as the spectrum is being shared, a more detailed concession is needed amongst competitors. Hence, fair rules and regulations must be adopted. Moreover, by sharing the spectrum, operators need to expose crucial information to competitors, such as traffic condition and bandwidth utilisation. Therefore, a regulator is needed to develop mutual trust with real-time updates to estimate the remaining resources accurately. With the implementation of SS, new network services or control functions are required to receive input and implement spectrum management and sharing decisions. Given that operators are normally bound by a long-term contract on 5G, a study on operators' willingness to share the spectrum is necessary. Furthermore, control of operators must be considered because several operators might opt for partial SS rather than full SS to prevent exposing internal network information. The placement of responsibility between sharing operators is another crucial issue in 5G.

SS classification can be divided into three parts: according to the spectrum access behaviour (cooperative or non-cooperative), network architecture (centralised or decentralised) and spectrum access methods (overlay or underlay) [72]. Several of the challenges were addressed by [70]. These challenges included spectrum management and spectrum assignment, metrics to quantify spectrum usage, interference coexistence and management, security and enforcement, protocols and standards and regulatory, policy and economic problems. The challenges that were not addressed by Furqan *et al.* are listed below.

- Radio software and hardware: Design of hardware and software for reconfiguration purposes, development of smart radio architectures and radio hardware to support operations in the mmWave band and design of sustainable low-powered devices and hardware that offer improved direction-finding, geolocation, etc.
- Experimentation, testing and standardisation: Development of test cases, virtual test beds to assess and model coexistence methods in large-scale environment and benchmark for designing test beds

The SS that is implemented in 4G uses a 'one-fits-all' architecture, which is unsuitable for 5G due to the various services offered, such as URLLC, eMBB and mMTC. Although numerous wireless nodes running these services are connected to the physical network, they have different requirements to be fulfilled. If spectrum resource allocation is not handled properly, users may experience deterioration in QoS, reduced data rates, unreliable transmission and high latency. A potential solution that was proposed by [82] is an SS scheme that uses the reservation-based sharing policy. This scheme is applicable to a 5G tenant-based cellular network with careful planning. The challenge presented in this study was the pursuit of a learning technique that has not yet been utilised for SS in multi-tenant cellular networks. The work was criticised for its wide use of stochastic learning, which is unsuitable for practical applications (such as in a power grid that requires high-speed protection).

The studies discussed in this section are compiled and presented in Table 3 chronologically.

C. RELATED WORK ON SPECTRUM SHARING TECHNIQUES

This section presents related work on SS techniques that are relevant to 5G networks. The techniques are categorised into main SS approaches based on network architecture, spectrum allocation behaviour and spectrum access method. Related SS studies on EE improvement are also discussed.

1) NETWORK ARCHITECTURE

An early work on SS based on network architecture was conducted by [84], who studied centralised SS using harmonised SDN-enabled approach (HSA). The system was utilised for synergistic SS by taking spectrum availability as the input. Incorrect decisions that are influenced by inconsistent QoS can be reduced using this method. This approach includes distributed sensing devices, BS and an SDN controller in the system. The centralised management minimises the SS processing by the BS. The SDN controller processes the information based on defined policies to allow PU or SU to enter and leave the network.

The spatial focusing effect was studied by [85] based on the trend of using massive MIMO and time reversal wideband in 5G networks. The spatial white space SS concept was designed to enable SS for concurrent multi-users without orthogonal resource allocation. Through Signal-to-Interference-plus-Noise Ratio (SINR) analysis, centralised and distributed protocols were proposed to study the congruency of the wide time reversal band and massive MIMO system. The main design consideration was the downlink network path for multiple users with a spatial focusing effect from the multi-path channel. The outcome showed the similar performance of the distributed and optimal centralised protocols with low complexity in the time reversal wideband and massive MIMO system.

Zhang *et al.* [86] proposed an interference graph and a game theoretic approach to achieve joint optimisation for decentralised SS for reducing complexity and maximising user satisfaction. Concurrent Best Response Iterative (CBSI) and Spatial Adaptive Play Iterative (SAPI) algorithms were used to converge Nash Equilibrium (NE) for either global or local optimisation. NE was used to measure user satisfaction across the network corresponding to the global or local maximiser. The global optimal solution was obtained using the SAPI algorithm with a large learning parameter and arbitrarily high probability. The authors also suggested an improvement of service experience through user allocation according to small BSs and spectrum band suitability.

2) SPECTRUM ALLOCATION BEHAVIOUR

A survey on the technical and economical views of cooperative and cognitive advanced SS and the differentiation classes of multi-level SS was conducted by Yang *et al.* [87]. The survey focused on spectrum trading and leasing, spectrum mobility, relaying, routing and harvesting. The SS schemes from the survey can enhance spectral and energy efficiency. The authors proposed a structure of 5G HetNets with the assumption that macro-cell eNodeB and SC eNodeB can use a cognitive application that can determine the capacity achieved and the SINR of the user equipment with its range. A poor SINR equipment is offloaded from MeNB. The cognitive SeNB also processes the requirement of offloading a user equipment to access the underutilised spectrum. The proposed advanced spectrum flow scheme was implemented on 5G HetNets, and it improved energy and spectral efficiency.

A hybrid SS system was introduced by [88]. The system is called Size-Negotiable Auction Mechanism (SNAM), and it combines auction and negotiation for multiple users. The SNAM system allows users to bid for the spectrum in per unit space and coverage areas as they prefer. To correctly model the interference, a mixed interference graph that can quantify up to five levels of interference was constructed to prove SNAM's rationality. The system can accommodate many BSs and provide fair spectrum competition in the case of small firms competing with large ones. It can observe the different sizes of large to small radius ratios for interference-free areas. Overall, the proposed mechanism performs better than the undirected graph method in terms of spatial efficiency, seller revenue and buyer satisfaction.

TABLE 3. Summary of previous survey/review papers related to SS with their focus and contributions.

Authors	Title	Survey/Review Focus and Contributions
Jonathan [79]	Cognitive Radio for 5G Wireless Networks	• Insight on challenges of expanding future research on CR in 5G • Enabling devices are expected to be developed in software defined devices • Specify the important aspects of cognitive terminal challenges such as adaptive prediction algorithms, seamless connectivity, fast and reliable reconfigurable hardware, and dynamic spectrum allocation
Jo et al. [78]	A Survey of Converging Solutions for Heterogeneous Mobile Networks	• Survey on challenges and solutions for converging current network to a heterogeneous mobile network • Suggest to combine three main convergences, CoMP and M2M integration for future research
Ding et al. [80]	On the Limits of Predictability in Real-World Radio Spectrum State Dynamics: From Entropy Theory to 5G Spectrum Sharing	• Identify when and where spectrum holes exist • Study predictable and unforeseeable underlying real-world RSS
Gupta and Jha [7]	A Survey of 5G Network: Architecture and Emerging Technologies	• Identify SS techniques which are distributed solutions and centralised solutions
Tehrani et al. [76]	Licensed Spectrum Sharing Schemes for Mobile Operators: A Survey and Outlook	• Survey on licensed SS mechanisms for cellular systems • Address the importance of SS and identify the gaps towards the design implementation of the most efficient sharing algorithms
Zhang et al. [81]	A Survey of Advanced Techniques for Spectrum Sharing in 5G Networks	• Integration issue of CR, D2D communication, in-band FD communication, NOMA, and LTE-U • CR needs to scan wider bandwidth which in turns making EE spectrum sensing scheme to be crucial in 5G networks
Hassan et al. [17]	Exclusive Use Spectrum Access Trading Models in Cognitive Radio Networks: A Survey	• Analyse three main dynamic sharing models: commons, shared use and exclusive use • Present overview of spectrum trading solutions for exclusive use and challenges on trading model viability assessment
Hu et al. [83]	Full Spectrum Sharing in Cognitive Radio Networks Toward 5G: A Survey	• Survey SS in CRNs based on SS scheme in four key steps: spectrum sensing, spectrum allocation, spectrum access and spectrum handoff • Present key enabling technologies related to 5G: FD spectrum sensing, spectrum-database based spectrum sensing, compressive spectrum sensing, carrier aggregation-based spectrum allocation
Ahmed et al. [70]	Towards Spectrum Sharing in Virtualized Networks: A Survey and an Outlook	• Present legal regulations (in USA, Europe and elsewhere) and trial activities for SS schemes (LSA, LAA and SAS) and studied the characteristics from inter-operator SS and virtualised network architectures perspective • Discuss on key challenges such on service differentiation, sharing of information and need for new network functions
Mishra et al. [72]	A Comparative Analysis of Centralized and Distributed Spectrum Sharing Techniques in Cognitive Radio	• Discuss on spectrum management, spectrum assignment and allocation

A paid sharing approach based on fluid models was proposed by Rattaro *et al.* [89] to encourage the SS behaviour of PUs in CR networks. The idea is that SUs must pay for spectrum utilisation, but priority is strictly given to PUs over SUs. Reimbursement is provided to affected SUs, but a cost is implied for the PUs' service provider. The approach was implemented by characterising the behaviour of the system using a fluid approximation stochastic model that considers pre-emptive situations with reimbursement, admission control decisions and multi-resource allocation. The proposed model can also benefit other economic scenarios by modelling the dynamic control queuing system with the said pre-emptive situations.

A study on unlicensed SS that allows an unlicensed band to coexist with WiFi for 5G was conducted by Bairagi *et al.* [90]. The proposed SS scheme is called LTE over an unlicensed band and improves users' Quality of Experience (QoE) whilst securing the necessary wireless system, such as WiFi. The proposed game-theoretic approach is a Virtual Coalition Formation Game (VCFG) that is divided into two sub-problems, where time sharing is solved by using the Kalai–Smorodinsky bargaining solution and resource allocation is implemented by the Q-learning algorithm. QoE is measured by the mean opinion score for selected applications, which are web browsing, video streaming and file downloading, because the requirements differ for every application. The proposed method can reduce unsatisfied users, achieve good fairness and manage WiFi systems properly.

3) SPECTRUM ACCESS METHOD

SAS is an emerging SS model that is currently gaining attention [70], [73], [76], [88], [91]–[93]. In the USA, SAS can be used by operators to access the 3.5 GHz military radar band for commercial use. This opportunity presented by SAS was exploited by [91] by proposing a scalable SAS framework that can manage the mMTC uplink interference to the incumbent with a low overhead. The database-driven dynamic spectrum access promoted by CR technology has issues in location privacy, where SUs must reveal their location in the process of querying and locating spectrum opportunities for them to use. This issue is encountered in white space geo-location spectrum databases for locating the available spectrum in TVWS. A multi-server Private Information Retrieval (PIR) was discussed by [94] as an enabler for private access to spectrum databases to protect the location information of SUs in database-driven SS. A database-driven CR network was designed to contain multiple synchronised spectrum databases that share the same content but are operated by different service providers. The authors concluded that information-theoretic location privacy can be efficiently provided to SUs via multi-server PIR.

The analytic hierarchy process approach of SS was discussed by [95] by addressing a solution to interference and performance improvement in 5G NR. The method is a multilevel hierarchical structure consisting of objectives, criteria and alternatives. It can find solutions to complex problems and was derived from a set of pair-wise comparison matrices. The method enables the calculation of user priority to access the spectrum without any conflict of interest amongst other SUs. It has efficient spectrum utilisation even with the increased number of users in the systems.

An efficient network sharing scheme that uses a two-time-scale hierarchical model for wireless network virtualisation resource management was studied by Jiang *et al.* [96]. The spectrum is sliced into sectors for PUs, SUs and tertiary users. Each slice has its own subchannel and power for every time slot. The PU's slice is allocated with its own subchannel and suitable power for guaranteed QoS, and the SU's slice is assessed in a static manner. The tertiary user's slice is integrated, and the idle spectrum band is assessed using a listen-before-talk scheme. The system is optimised with the Lyapunov algorithm for large-time-period frequency allocation, the time-slot subchannel and power scheduling algorithms. The scheme focuses on packet delay, data rate and IoT throughput for the three types of users. Simulation of the proposed scheme showed effectiveness in terms of delay and power allocation (PA) optimisation, but fairness amongst users has not been investigated yet.

The dynamical advance access SS method for public and dedicated telecommunication operators was introduced by Lin *et al.* [97] to ensure the QoE of SU. The system was modelled based on a finite-state Markov chain for the analysis of the state transition model. The system introduces an enhanced mobility management entity that is responsible for SS management. The BS of both operators is set so they can only execute tasks from their own users whilst all service requests and dynamic spectrum access are performed by the central BS. The results showed that the queuing time and proposed architecture are better than those of the shortest queue length access and QoE-driven access methods because the design considers the variation in channel condition and service state, resulting in better QoE performance.

A new hybrid spectrum access method was introduced by [98] to combine exclusive access and pooled spectrum access. This hybrid design aggregates the low-frequency carrier for exclusive access and the high-frequency carrier for spectrum pooling. The method is reminiscent of the LAA structure in the Third Generation Partnership Programme (3GPP) system that aggregates the licensed carrier with the unlicensed spectrum. The proposed system was compared with exclusive and pooled systems for benchmarking. The results showed that the proposed approach provides better performance to the average user and a slightly better throughput compared with fully licensed and fully pooled approaches, respectively.

One of the promising multiple-access techniques, NOMA, was recently recognised to encourage SS with a significant improvement in the spectral efficiency of mobile communication networks [99]. The technique is based on the power domain, unlike the previous generation of mobile networks that rely on the time/frequency/code domain. The technique also allows SS for multiple users in the same time-frequency resource block, where the set of users served by a BS via NOMA is known as a user cluster. Many researchers have demonstrated that NOMA is compatible with numerous 5G techniques. Latest innovations and applications of NOMA have been documented in the IEEE Access Special Section Editorial [100] to bridge the gap between theory and practice in designing NOMA for 5G. A study on the EE of PA was conducted by [101] for a MIMO–NOMA system with multiple users in a cluster and considers the QoS of all users. The authors proposed an optimal PA strategy to solve the EE maximisation problem when feasible. Moreover, a low-complexity user admission protocol was proposed where users are admitted in ascending order according to their power requirement (one by one) to satisfy their QoS requirements. The recent work of [102] presented a large cellular Poisson network that employs NOMA in the downlink and addresses the challenges in NOMA for multiple users with the use of SIC for decoding at each user. Three models for NOMA user clustering were proposed to highlight the importance of choosing network parameters and constraints and ordering to balance the cell sum rate and fairness requirements. The authors also showed that efficient interference-aware user clustering is important in improving performance in terms of maximising the cell sum rate. The cell sum rate can be maximised by allocating all resources (power in the NOMA network) to the best user [103].

Three key performance metrics have been identified in the development of a sustainable 5G system; these three are spectrum utilisation, energy consumption and cost efficiency. SS in 5G scenarios has been studied for many applications, such as improvement of EE and multiple spectrum access. The energy issue for the SS of cognitive SCs was studied by [104] in relation to the Energy-aware Dynamic Spectrum Sharing (EDSS) algorithm. They contributed to literature on the selection of the most appropriate mode in the downlink for all individual SCs with theoretical upper bound performance. A known problem in EE maximisation for underlay and overlay SS is the non-convex fractional problem of the resource allocation system. Considering the scenario models of CR and D2D communication, Zappone *et al.* [105] proposed an optimal resource allocation policy for the SU through a suitable reformulation of the original non-convex fractional problem in the underlay model. For the overlay model, the same authors proposed two algorithms but with trade-off between complexity and optimality claims. An SS approach that conforms with green communication and uses the zonal approach was presented by [106] for primary transmitter (PT)-forming D2D communication links with multiple primary receivers (PRs). The method has a low energy consumption at the PT with optimised transmission power within a zone that adequately meets the target rates demanded by PRs. The method was implemented using an iterative approach. It can improve the EE of the system and enhance the battery lifetime of the PT.

Zhou *et al.* [107] conducted a study on SS that focused on vehicle communication, specifically D2D communication. In their research, vehicle communication using SS was done to achieve an immersive experience with dedicated short-range communication. The architecture was explored for licensed and unlicensed spectra for improved efficiency and flexible usage. The proposed design also solves the vehicular-D2D (v-D2D) underlay shared spectrum resource problems of inconsistent TVWS spectrum due to location and time. The proposed architecture consists of four components, which are heterogeneous vehicular network, radio resource sharing cloud, the Internet and channel access. Moving forward, the research focused on mobility for vehicle communication and SS management for software-defined solutions.

For a more intelligent SS that supports the requirements of 5G wireless networks (high spectrum efficiency, massive connectivity, low latency and improved fairness), the integration of NOMA and CR was investigated by [108]. State-of-the-art cognitive NOMA architectures, namely, underlay and overlay NOMA and CR-NOMA, were also discussed. NOMA principles exploit power domain multiplexing at transmitters for signal combination and SIC at receivers for signal detection. By integrating CR and NOMA, spectrum efficiency can be enhanced from different perspectives, such as improved spectrum efficiency, massive connectivity, low latency and enhanced fairness. The authors proposed cooperative relying strategies in cognitive NOMA to improve reception reliability in addressing inter-network and intra-network interferences that cause major degradation in the performance of cognitive NOMA networks. The method can also be used to improve the cost of installing relays and has the potential to decrease outage probabilities significantly.

SS and spectrum aggregation utilising enhanced CRNs (E-CRNs) for sharing licensed TVWS spectrum, the LTE TDD band and unlicensed spectrum bands were studied by [93]. The E-CRNs framework was embedded with Dynamic Spectrum Management (DSM) and the water-filled algorithm for the spectrum access method. The proposed E-CRNs system model implements imperfect spectrum sensing that guarantees PU priority and allows the SU interference during transmission to be controlled rather than perfect spectrum sensing which contributes several limitations. Furthermore, dynamic spectrum aggregation and spectrum lean management were introduced to reduce the interference to the WiFi network and maximise the system output, respectively. The numerical results proved that high system QoS performance, which contributes to good outage probability, sum rate and spectrum efficiency, is achieved. Holland [109] studied the parameter performance of the TVWS band, especially during the aggregation of TVWS resources. They assessed the experiment with two conditions, which are mobile broadband downlink and indoor broadband provisioning. A study on link performance test was also conducted to identify the strength of using TVWS for indoor environment. The experiment was modelled using Carlson RuralConnect WSD, which was coded using the coded OFDM waveform and multiple modulation techniques that can be selected by the devices to evaluate the TVWS band's availability and capacity.

In addressing spectrum scarcity using CR technology, traffic congestion can only be alleviated over the air, and the strain in the case of limited backhaul cannot be reduced. The heavy burden at the backhaul can be relieved using fog-computing-based wireless caching, which can be incorporated into CR paradigms for improved performance. The primary transmission can be protected from unintended secondary interference using an opportunistic spectrum access, namely, the guard zone and interference cancellation-based opportunistic spectrum access proposed by [110]. The method can enhance the spectrum accessibility of SUs.

Table 4 summarises the aforementioned SS techniques with their focus, contributions and key features and sorts them according to their SS approach, SS technique and year of publication.

IV. PROMISES OF COGNITIVE RADIO

CR technology is one of the promising technologies that enable open SS for 5G. This emerging technology can satisfy the strict spectrum requirement of 5G networks. It has cognitive potential, is reconfigurable and its transmission parameters can be adjusted according to environment characteristics. The functions of CR include spectrum sensing, management, mobility and sharing. Spectrum sensing is a key function to detect the unused spectrum (spectrum hole). Spectrum hole is the temporary space-time-frequency that exists, is not used by any PU or SU and changes according to the time and place [77]. Spectrum management is utilised to determine the best channel for establishing communication based on user necessities. Spectrum mobility moves the spectrum with a low priority to the next vacant channel whenever PU is not in range. SS distributes the spectrum amongst SUs accordingly.

TABLE 4. Summary of previous SS techniques with their focus, contributions and key features.

Authors	Year	SS approach	SS technique	Focus and contributions	Key Features
Akhtar et al. [84]	2016	Network architecture	Centralised	• HSA is utilised by taking input of availability of spectrum. • System includes distributed sensing devices, BS and SDN controller.	Reduced influence of inconsistent quality of signal
Jiang et al. [85]	2017	Network architecture	Centralised and distributed	• The spatial focusing effect is studied based on the trend of using massive MIMO and time-reversal. • Spatial white space SS concept is designed to enable sharing of spectrum for concurrent multi-user without orthogonal resource allocation.	Multi-user, spatial white space
Zhang et al. [86]	2017	Network architecture	Decentralised	• Propose an interference graph and game theoretic approach to achieve joint optimisation on decentralise SS. • CBSI and SAPI algorithms are used to converge NE for either global or local optimisation.	Game theory, interference graph
Yang et al. [87]	2016	Spectrum allocation behaviour	Cooperative	• Survey on technical and economic view of cooperative and cognitive advanced SS, and differentiation classes of multi-level SS.	Interference (SINR)
Wang et al. [88]	2017	Spectrum allocation behaviour	Cooperative	• Introduce a hybrid SS system which combines auction and negotiation called SNAM • Construct mixed interference graph which can quantify up to five level of interference.	Interference graph, multi-user
Bairagi et al. [90]	2018	Spectrum allocation behaviour	Cooperative	• Study on local thermal equilibrium on unlicensed band. • The proposed game-theoretic approach is a VCFG that is divided into time sharing, solved using Kalai-Smorodinsky bargaining solution and resource allocation is solved by and Q-learning algorithm.	Game theory, QoE
Rattaro et al. [89]	2018	Spectrum allocation behaviour	Non-cooperative	• Propose paid sharing approach which SUs pay for spectrum utilisation but PUs have strict priority over SUs. Reimbursement for affected SUs implying some cost for PUs service provider.	Multi-resource
Mach and Becvar [104]	2017	Spectrum access method	Overlay and underlay	• EDSS algorithm – in selecting the most appropriate mode in downlink for all individual SCs	EE
Zappone et al. [105]	2017	Spectrum access method	Overlay and underlay	• Optimal resource allocation policy for the secondary system for underlay by means of a suitable reformulation of the original non-convex fractional problem. • Propose two algorithms with a trade-off between complexity and optimality claims for overlay.	EE, D2D
Gandotra et al. [106]	2018	Spectrum access method	Simultaneous (overlay or underlay)	• SS approach that is in conformity with green communication using zonal approach with PT, forming D2D communication links with multiple PRs • Use iterative approach for optimal transmission power consumption to service each PR in respective zone.	Green, D2D, EE, multi-user
Zhou et al. [107]	2017	Spectrum access method	Underlay-shared	• Focus study on vehicle communication using SS to achieve immerse experience which implemented dedicated short-range communication. • Explore on architecture for both licensed and unlicensed spectrum.	TVWS, v-D2D
Lv et al. [108]	2018	Spectrum access method	Overlay and underlay NOMA	• Discuss on the state-of-the-art of cognitive NOMA architectures (underlay and overlay NOMA, and CR-NOMA). • Propose cooperative relying strategies in cognitive NOMA to improve reception reliability and cost of installing relays.	Interference (SIC), outage probability

The handover procedure for CRN was described in detail by [71] as follows. Upon the arrival of PU, SU has to vacate the occupied channel and is forcibly terminated. A method called fraction guard channel assignment performs this task,

TABLE 4. ***(Continued.)*** **Summary of previous SS techniques with their focus, contributions and key features.**

Costa et al. [100]	2018	Spectrum access method	NOMA	• Review on NOMA • Allow sharing of spectrum for multiple users in the same time-frequency resource block, where the set of users served by a BS via NOMA is known as user cluster.	Multi-user
Zeng et al. [101]	2018	Spectrum access method	NOMA	• Propose optimal PA strategy to solve EE maximisation problem • Done on MIMO-NOMA system with multiple users in a cluster	Multi-user, QoS, EE
Ali et al. [102]	2019	Spectrum access method	NOMA	• Propose three models for NOMA users' clustering	Multi-user, interference (SIC)
Jayawickrama et al. [91]	2018	Spectrum access method	SAS	• Scalable SAS framework that is able to manage the mMTC • Issues on location privacy where SUs have to reveal their location	Scalable SAS, mMTC
Grissa et al. [94]	2018	Spectrum access method	SAS	• Multi-server PIR for private access to spectrum databases • Database-driven CR networks includes multiple spectrum databases that sharing the same content and operated by different service providers	TVWS, database-assisted
Kalidoss et al. [95]	2018	Spectrum access method	Hierarchical	• Address a solution for interference and performance improvement in 5G NR. • The method is a multilevel hierarchical structured which can find a solution for complex problem that is derived from a set of pair-wise comparison matrix.	Improve overall interference, multi-user
Jiang et al. [96]	2018	Spectrum access method	Hierarchical	• Study on the efficient sharing network using two time scale hierarchical model for wireless network virtualisation. • Lyapunov optimisation is utilised for large-time-period frequency allocation, time-slot subchannel and power scheduling algorithms.	QoS
Jia et al. [110]	2018	Spectrum access method	Interweave (opportunistic)	• Use opportunistic spectrum access to protect primary transmission from unintended secondary interference • Able to enhance spectrum accessibility of SUs.	Interference (to protect primary)
Rebato et al. [98]	2017	Spectrum access method	Exclusive	• New hybrid spectrum access method are introduced which have separation between mmWave band scheme using exclusive access. • The proposed system is compared with exclusive only and pooled only system for benchmarking.	mmWave
Lin et al. [97]	2017	Spectrum access method	Dynamic	• Study on dynamical advance access SS method for public and dedicated user. • The system is modelled based on finite state Markov chain for analysis of the state transition model.	QoE
Zhang et al. [93]	2018	Spectrum access method	Dynamic	• SS and spectrum aggregation are utilised on E-CRNs for sharing licensed TVWS spectrum, LTE TDD band and aggregate the unlicensed spectrum bands. • The framework E-CRNs are embedded with DSM and water-filled algorithm for spectrum access method.	Allow SU interference, reduce WiFi interference, TVWS, QoS

resulting in throughput increment of unlicensed users. However, the value cannot be attuned effectively. Four metrics were identified by [111] to present the performance of short-term and long-term spectrum handover. The metrics are link maintenance probability, number of spectrum handover, switching delay and non-completion probability. The complete CR cycle is shown in Figure 9.

A survey on cognitive and cooperative SS schemes was performed by [87], with focus on enhancing spectral and energy efficiency in a cost-effective manner. The approaches to SS were discussed from two perspectives: economic marketing perspective, which emphasises spectrum trading, spectrum leasing and multi-tier spectrum trading and leasing, and cross-layer technical implementation perspective, which discusses spectrum mobility, spectrum relaying, spectrum routing and spectrum harvesting. The buying and selling process and exchanging the rights to the radio spectrum are collectively known as spectrum trading, which also enhances

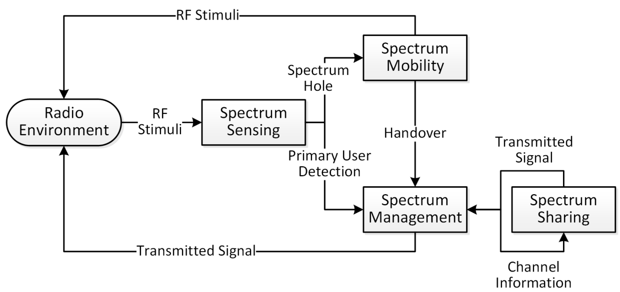

FIGURE 9. CR functions' cycle (adapted from [71]).

the utilisation of the radio spectrum. SS based on game theory is one of the market-driven spectrum trading schemes. Spectrum leasing is the act of leasing parts of the bandwidth by the PU who owns a given licensed spectrum bandwidth to SUs in exchange for economic revenue or technical cooperation. Multi-tier spectrum trading and leasing were proposed in [87]. They have different tiers (upper, medium and low) to represent long, medium and short terms, respectively. In CRN, spectrum mobility enables the suspension of SU's transmission to vacate the channel in order for PU to reclaim its licensed channel that has been temporarily leased to SU. The main aim is to guarantee the QoS and performance of PUs and SUs during the switching process. The ongoing data transmission of the SU must be transferred from the current channel to an alternative free channel via a process known as spectrum handoff. In spectrum mobility, PU has a higher priority than SU. Thus, SU must immediately vacate the licensed channel once it causes interference. The SU may experience spectrum mobility due to the degradation of link quality. Spectrum relaying can be enabled with relay-assisted protocol for spectrum mobility in CRN, where each SU has more than one connection path to the BS through dynamic spectrum relaying. In wireless communication, spectrum routing is a series of channel switching decisions by TVWS sharing subscribers when they foresee channel availabilities. Meanwhile, spectrum harvesting is a new idea for CRN, where SS occurs between PUs and cognitive users as the SUs. To maximise spectrum utilisation, a new service provider dedicated for SUs was introduced; it harvests the available spectrum bands with CR capabilities.

Spectrum access for dynamic sharing models is categorised as common, shared use and exclusive use. For CRs, the most promising model for satisfying the spectrum needs of users is the exclusive-use model with spectrum trading solutions, such as game theory, market equilibrium, classical optimisation and their hybrid. The overview of the said trading model together with its features, limitations, feasibility and stability of the pricing solution was presented by [17].

Service provisioning challenges, such as providing channel access opportunities for new service requests and guaranteeing continuous connections for ongoing flows until service completion, exist in wireless networks. These challenges can be addressed with the Dynamic Channel Reservation (DCR) algorithm and Dynamic Spectrum Access (DSA) scheme with three access privilege variations to explore the advantages of channel reservation in performance improvement in error-prone channels [112]. DCR is used to reserve a dynamically adjustable number of channels for uninterrupted services to maintain service retainability for current users. Alternatively, it is also used to enhance channel availability for new users. The DSA scheme has a DCR algorithm embedded in it to enable spectrum access for PUs and SUs based on their licensed shared access. In addition, the DSA scheme is utilised to investigate the performance of CRN in homogeneous and heterogeneous channel failures by using the continuous-time Markov chain model.

CR is known to create opportunities for SUs to use spectrum holes or white spaces that are not being used by PUs, but the main challenge is to recognise without fail the specific time and location of spectrum hole existence [80]. Previously, CR-based SS used opportunistic PU-SU access in unlicensed bands (such as TVWS) only, but the 5G requirement demands for sharing of both licensed and unlicensed bands. A new E-CRN based on SS and spectrum aggregation for 5G was introduced by Zhang *et al.* [93]. They exploited the licensed spectrum of PU networks, including TVWS and LTE TDD bands, and the unlicensed spectrum from industrial, scientific and medical bands. The framework for E-CRN includes DSM for licensed SS and unlicensed spectrum aggregation. The method can control harmful interference but with trade-off between sharing and aggregation efficiency. Thus, spectrum-lean management was introduced to achieve DSM. In addition, a water-filling algorithm was proposed to access the available spectrum dynamically and assign system traffic offloading to the shared and aggregated spectrum bands. The authors in [93] also studied the co-existence of E-CRN and WiFi.

The CR in the 5G environment has the following characteristics: interoperability, context awareness, learning ability, self-optimisation, dynamic spectrum management, adaptive decoding and self-healing. It can be realised by using a CR terminal with several components, such as a software-defined device, a geo-locator, a learning system, a policy database, sensors, optimisation algorithms and the cognitive engine itself [79]. CR technology was initially implemented using half-duplex (HD) radio due to the hardware and software complexities of the superior FD communication [113]. After five decades, this FD CR technology gained serious attention with the recent advances in signal processing, machine-to-machine communication and deep learning methods. A survey on SS in CR networks was conducted by [83] in four key steps: spectrum sensing, allocation, access and handoff; the key enabling technologies related to 5G were presented. The technologies were FD spectrum sensing, spectrum database-based spectrum sensing, compressive spectrum sensing and carrier aggregation-based spectrum allocation. Spectrum prediction and spectrum sensing can be used to reliably identify when and where spectrum holes exist. Several of the applications of spectrum prediction in 5G SS include cost-efficient wideband carrier aggregation, dynamic frequency selection and predictive interference mitigation [80]. The theory of interplay between predictable and unforeseeable underlying real-world RSS was studied by [80]. Technical guidance on how to apply the predicted RSS to the design of future wireless communication was provided.

In terms of energy, the HD technique consumes relatively minimal energy due to its low complexity. Although the FD technique can enhance the gain in throughput [114], it is uncertain whether FD can outperform HD in EE. A comparative study was conducted by Li *et al.* [115] in 2018 to analyse both techniques. The authors proposed an adaptive SS scheme that utilises the HD and FD of CR technology. Their analysis showed that the adaptive scheme has a higher EE than either techniques alone. In 2019, the authors developed a polarisation-enabled FD hybrid SS scheme [116] that guarantees a sufficiently small collision ratio for PUs and a larger throughput improvement compared with traditional schemes. Another study on EE was conducted by Park and Hwang [117] for cognitive femtocells and picocells. They proposed an optimal EE PA using sensing-based SS for uplink multiple cognitive femto users operating in multiuser MIMO mode at the same frequency bands. Data transmission to a femto BS is performed in the presence of a pico BS and multiple pico users. The design adopts a user-wise EE with Pareto optimisation. An additional power constraint is introduced to convexify the non-convexity optimisation problem without losing global optimality. Each femto user's EE is quasi concave.

To improve EE in the CR network, [118] and [119] proposed an energy-harvesting-aided spectrum sensing and data transmission scheme by turning the harmful interference from PU into favourable factors for improving sensing performance and providing power to SUs. The scheme was developed by combining the individual and cooperative sensing of multi-users corresponding to the PUs's strong and weak signals. A study on the trade-off of spectral EE in CR was conducted by [120] for link and system levels at various Signal-to-Noise Ratio (SNR) values. The amount of energy needed to achieve benchmarked CR spectral efficiency at the link level was investigated for low and high SNRs. Furthermore, the interference constraint was studied to protect PR. The results showed that at a low SNR, constraining the energy level at average power provides a better EE than that at peak power. However, neither power constraint poses an impact on EE at a high SNR. At the system level, extreme value theories were implemented to study the CR EE for indoor environments, specifically in the uplink CR-cellular network. The result showed high spectral efficiency for a low PR, but the spectral efficiency rapidly drops as the number of PR increases. However, this situation can be compensated for by reducing the threshold of the interference, which can be achieved by increasing the secondary receiver within the range of the secondary transmitter.

Wang *et al.* [121] considered the potential benefits of using massive MIMO in underlay CRNs. They derived the distribution of SINR for downlink transmission in secondary network (SN) by considering the downlink multi-user MIMO transmission in the PU network. The measure was for the performance analysis of any finite number of antennas. An asymptotic analysis at the primary and secondary BSs for massive antenna arrays was also presented, particularly on the effect of a large number of PUs and imperfect channel state information on SN. Their analysis showed that the usage of large antenna arrays improves the power efficiency in SS networks. The application is for SS in multi-user MIMO primary and multiple-input single-output SN using the combination of primary and secondary BSs with single-antenna PU and SU, respectively. A comprehensive system analysis was performed to mathematically evaluate the lower bound of the average achievable rate.

A study by [113] presented the challenges in CR technology, including enhancing spectral efficiency and multi-user interference starting from HD and FD and how to implement them efficiently in 5G networks. The authors also addressed several recent works, specifically on cognitive and FD networking, that focused on security, minimising delay, resource optimisation using the PA algorithm and asynchronous CR with the new MAC protocol. Physical layer security was addressed by [122] by proposing a cognitive security concept but with several challenges, such as condition detection, correct statement identification and security mechanism for many resources. Khan *et al.* [123] discussed the requirements, design challenges and review of routing and MAC protocols for CR-based smart grid systems. The mutual interference for spectrum users in the same band can be reduced by using a cognitive radar with spectrum sensing and transmission notching abilities. Ravenscroft *et al.* [124] conducted a study on the case where another spectrum user moves in the frequency during the radar's coherent processing interval, and the radar emission is inherently robust to sidelobes that otherwise arise for spectral notching. The interference considered was in-band OFDM signals that hop around the band, and the fast spectrum sensing algorithm determined where notches are required. The efficacy factors for the proposed algorithm are the shape of the notch, maintaining the notch depth when generating the final emitted waveform, transmitter distortion and Doppler smearing due to notch hopping.

In CRN, a reliable spectrum detection depends on the accuracy of PU location. A deep sensing algorithm was studied as a joint estimation for applications that require spectrum and location awareness. The emission state of a PU is identified by estimating its evolving positions [125]. For mobile PUs, effective spectrum sensing can be realised by tracking their locations incessantly, and the location information can be utilised in cognitive performance optimisations. Another study was carried out to propose a wideband SS and compress the sensing method based on frequency-domain cyclic prefix autocorrelation. The study provided an accurate detection of OFDM-based primaries in wideband CR systems [126]. The method can overcome the noise uncertainty and frequency-selective multi-path channel effects in realistic wideband communication scenarios and can utilise the spectral domain sparsity. In addition, the method can be combined with other wideband spectrum sensing approaches, such as sub-band energy detection. A wideband sensing platform can also run parallel sensing processes for different frequency channels and diverse types of primaries.

Spectrum decision and prediction were studied by [127] on the basis of a context-aware cloud-based spectrum monitoring system that utilises the benefit of the crowd-sensed data of static and mobile users with the cooperation of multiple SUs. The aim was to overcome the problem faced by SUs in finding idle frequency bands by using stand-alone spectrum sensing that is prone to fading, shadowing and noise uncertainty effects and leads to undetected PU activity. The crowd-sensed data contained spectrum data and contextual information, such as time, location and building complexity. Current and future channel statuses were predicted using supervised learning methods, such as k-nearest neighbour, support vector machine and artificial neural network.

CR is very promising for sharing the licensed spectrum and enhancing system throughput. System robustness against errors can be improved by increasing the number of decoding blocks, but this will also increase the delay. By utilising the SS model, the authors in [128] proposed a minimisation of the outage probability over block-fading channels for optimal resource allocation under the PU outage constraint. The aim was to address the challenge of finding a trade-off between tuning the decoding blocks' length and sharing the spectrum. The algorithm is based on alternating optimisation, which uses a problem with a verified strict quasi-convex structure. Additional sensing information can be obtained, and system performance is analysed under the CR constraint with or without sensing information. Another outage analysis was performed by [129] to investigate the outage performance of cellular underlay SS by exploiting multi-antenna and multi-user diversity using the transmit antenna selection algorithm and opportunistic scheduling. The authors derived the outage performance for a PU simultaneously with that for an SU PA.

On the architecture side, Lorenzo *et al.* [130] proposed a novel collaborative cognitive dynamic network architecture that incorporates cognitive capabilities to exploit the underutilised spectrum in a flexible and intelligent manner. The architecture leverages the density and heterogeneity of wireless devices to provide ubiquitous Internet connectivity. The design principles are aligned with the 5G functionality requirements, which are energy and spectrum efficiency, scalability, dynamic reconfigurability, support for multi-hop communication, infrastructure sharing and multi-operator cooperation. The work also illustrated the benefits of the cognitive dynamic network architecture in tackling user associations for data and spectrum trading with low complexity and enabling self-organising capabilities.

The transmission of video data for future multimedia traffic was studied in [131] by using CR to meet the critical spectrum demands. Data were transmitted over underlay cellular CRN with cooperative diversity. To ensure the QoS of primary transmissions and prevent packet loss due to PU interference and channel fading, the authors used RaptorQ code as the application layer forward error correction scheme. Additionally, for the efficient utilisation of the licensed channel and robust video transmission, the authors employed different time-sharing ratios ranging between direct and best indirect links.

For an environment-friendly network, Sboui *et al.* [132] proposed low complexity profit maximisation algorithms for CR cellular networks consisting of collaborated primary network (PN) and SN, with a certain threshold constraint for carbon dioxide (CO_2) emission that is controlled by a regulator. The optimisation was based on decentralised and centralised approaches, in which renewable energy availability and roaming cost are important parameters for network profits. In the collaboration CRN, PN and SN maximise their own profits whilst meeting the PN's QoS and the imposed total carbon dioxide emission constraint. The PN switches off several of its BSs to reduce carbon footprints, and the corresponding users are roamed to the SN's BSs. In return, the SN receives certain roaming cost and is free to exploit the PN's spectrum. The spectrum is managed dynamically between the two networks either by sharing or leasing, depending on the profit per CO_2 emission of the PN's BSs. CR creates endless possibilities in sharing a limited spectrum band more effectively, with the aim of improving EE and spectrum efficiency, optimising power utilisation and eliminating interference with promising integration with FD technology.

Table 5 summarises all related CR studies on SS together with their focus, contributions and key features. The studies are sorted according to their CR functions and year of publication.

V. ISSUES, CHALLENGES AND FUTURE RESEARCH DIRECTIONS

Network system and architecture are developing rapidly. With 5G deployment, promising network improvements in terms of speed for future IoE-enabled applications, problems and solutions must be identified accordingly. To support the development and requirement of 5G, challenges and issues are presented in this section.

A. SPECTRUM SHARING

Dense areas are created due to the emergence of heterogeneous devices and the need for high-capacity data transmission. Jo *et al.* [78] conducted a detailed survey on the challenges of and solutions to converging the current network to a heterogeneous mobile network for performance improvements. Three types of converged mobile networks exist: device, protocol and service convergence. These converged mobile networks offer high spectrum efficiency and coverage in CoMP M2M HetNet. These future networks will also have integration issues in CR, D2D communication, in-band FD communication, NOMA and LTE-U, as addressed in [81]. For example, CR needs to scan a wider bandwidth, which makes the EE spectrum sensing scheme crucial in 5G networks.

TABLE 5. Summary of previous CR work in SS with their focus, contributions and key features.

Authors	Year	CR functions	Focus and contributions	Key features
Yang et al. [87]	2016	CR survey	• Survey on cognitive and cooperative SS scheme • Focus on enhancing spectral and energy efficiency in cost effective manner • Address issues on 5G cognitive HetNet	Spectrum trading and leasing
Jonathan [79]	2014	CR survey	• Explain the characteristics of CR in 5G environment • Discuss issue on 5G CR terminal	Spectrum optimisation
Shikh-Bahaei et al. [113]	2018	FD in CRN	• Present challenges on CR technology, including enhancing spectral efficiency and multi-user interference, starting from HD, FD and how to implement them efficiently in 5G network	FD for spectral efficiency, interference
Ding et al. [80]	2015	Sensing	• Use spectrum prediction and spectrum sensing to identify the existence of spectrum holes • Discuss on the cost efficient wideband carrier aggregation, dynamic frequency selection and predictive interference mitigation	Spectrum hole, spectrum prediction and spectrum sensing
Gao et al. [118], [119]	2016, 2018	Sensing	• Propose an energy-harvesting-aided spectrum sensing and data transmission scheme • The method is to turn harmful interference from PU to favourable factors of improving the sensing performance and providing the power for SU	Energy-harvesting-aided spectrum sensing; interference to improve performance
Khan et al. [123]	2017	Sensing	• Discuss the requirements, design challenges and review of routing and MAC protocols for CR-based smart grid systems • Reduce mutual interference for spectrum users in the same band using cognitive radar with spectrum sensing and transmit notching ability	CR-based smart grid systems; mutual interference
Ravenscroft et al. [124]	2018	Sensing	• Study on the case of spectrum user moves in frequency during the radar's coherent processing interval • Address issues on spectrum sensing with estimation approaches	Spectral nothing; OFDM signals interference
Li et al. [125]	2015	Sensing	• Study on a deep sensing algorithm as a joint estimation for applications which require spectrum and location awareness • Identify the emission state of a PU by estimating its evolving positions	Deep sensing spectrum detection
Dikmese et al. [126]	2017	Sensing	• Propose a wideband SS and to compress sensing method based on frequency-domain cyclic prefix autocorrelation • Able to provide accurate detection of OFDM-based primaries in wideband CR systems	Wideband CR SS; compress sensing; OFDM
Shirvani and Shahgholi [127]	2019	Sensing	• Study on spectrum decision and prediction based on context-aware cloud-based spectrum monitoring system • Use the benefit of crowd-sensed data of static and mobile users with multiple SUs • Address issues on spectrum sensing using crowd sensing	Context-aware cloud-based spectrum monitoring system; spectrum decision and prediction
H and K [71]	2019	Handover (mobility and management)	• Describe CRN handover procedure • Address issues on spectrum handover, spectrum allocation and management, spectrum management functions	Cooperative spectrum handover, cooperative spectrum sensing during handover
Zhao and Swami [111]	2007	Handover (mobility and management)	• Identify four metrics to represent short-term and long-term spectrum handover performances	Spectrum handover performance
Yılmaz et al. [122]	2017	Management	• Propose cognitive security concept • Identify several challenges such as condition detection, correct statement identification and security mechanism for many resources	Cognitive security concept
Lorenzo et al. [130]	2017	Management	• Propose a novel collaborative cognitive dynamic network architecture • Exploit underutilised spectrum in an intelligent way • Address issues on CRN architecture	Spectrum trading

Open research challenges in database-driven CRNs for SUs' location privacy were acknowledged by [94]. The challenges are private collection of SUs' usage data, partial replication of database content, coexistence and interference amongst SUs, multi-SU coordinated queries, protecting the privacy of PUs and spectrum access policy enforcement.

TABLE 5. *(Continued.)* **Summary of previous CR work in SS with their focus, contributions and key features.**

Sboui et al. [132]	2016	Management	• Propose a low complexity profit maximisation algorithms for CR cellular network • Use collaboration of PN and SN with certain threshold constraint for CO_2 emission	Green CR; decentralised and centralised optimisation of PN and SN
Park and Hwang [117]	2016	Sensing, sharing	• Study on EE for cognitive femtocells and picocells • Propose an optimal EE PA using sensing-based SS for uplink multiple cognitive femto users operating in multiuser MIMO mode at the same frequency bands	Sensing-based SS
Alabbasi et al. [128]	2017	Sensing, sharing	• Propose a minimisation of the outage probability over the block-fading channels • Address issue on outage analysis for cognitive SS	CR PU outage constraint
Haider et al. [120]	2015	Sharing	• Study on the trade-off of spectral EE in CR for link and system levels at various SNR values • Study on amount of energy needed to achieve benchmarked CR spectral efficiency at the link level	Spectral efficiency in CR; PR and interference
Hassan et al. [17]	2017	Sharing	• Overview of exclusive-use model with spectrum trading solutions • Discuss on game theory, market equilibrium and classical optimisation, and their hybrid	Spectrum trading solutions
Balapuwaduge et al. [112]	2018	Sharing	• Propose DCR algorithm and DSA scheme with three access privilege variations • Use channel reservation to improve performance in error-prone channels • Address issues on channel allocation in dynamic spectrum reservation	Spectrum reservation
Zhang et al. [93]	2018	Sharing	• Propose a new enhanced CRN based on SS and spectrum aggregation • Exploits licensed spectrum of PU networks (including TVWS and LTE TDD bands) and unlicensed spectrum from industrial, scientific and medical bands	SS and spectrum aggregation
Hu et al. [83]	2018	Sharing	• Survey on SS in CR networks in four key steps: spectrum sensing, spectrum allocation, spectrum access and spectrum handoff • Discuss general CRN issues and spectrum allocation issues	Spectrum sensing, spectrum allocation, spectrum access and spectrum handoff
Li et al. [115]	2018	Sharing	• Propose an adaptive SS scheme utilising both HD and FD of CR technology • Address issues on SS in FD CRNs	HD and FD SS
Wang et al. [121]	2017	Sharing	• Use massive MIMO in underlay CRNs • Consider the downlink multi-user MIMO transmission in the PU network	Power efficiency in SS networks
Ali et al. [131]	2018	Sharing	• Study on video data transmission for future multimedia traffics • Use CR to meet the critical spectrum demands	CR for video data demand
Khan and Singh [129]	2019	Sharing	• Investigate outage performance of cellular underlay SS • Use transmit antenna selection algorithm and opportunistic scheduling to exploit multi-antenna and multi-user diversity • Address issue on outage analysis for cognitive SS	Outage analysis; multi-antenna, multi-user

For SS techniques, several gaps must be bridged to realise efficient SS in the 5G environment. A dense network leads to multi-user interference, security problems [122] and service deterioration because of the high competition for limited shared resources. Furthermore, the need for large bandwidth by heterogeneous devices leads to the lack of spectrum availability. Despite the availability of numerous SS techniques, accurate spectrum sensing is required to reduce the interference. Determining the most efficient design implementation of sharing algorithms is another issue, as identified by [76]. For SS in a virtualised network, several key challenges were enumerated by [70], and these included addressing service differentiation, sharing of information, new network functions, long-term contracts, management and control and responsibility assignment. Nonetheless, improvements in the hardware level are still needed to create a device that can overcome propagation losses and interference.

Dynamic SS is open to several policy-domain challenges. Interdisciplinary research is required for spectrum usage and access to manage the sharing of limited spectrum resources efficiently in the fields of market- and non-market-based mechanisms. Other open problems in SS include spectrum management and spectrum assignment/allocation, metrics to quantify spectrum usage, interference coexistence and management, security and enforcement, radio software and hardware, protocols and standards, experimentation, testing and standardisation and regulatory, policy and economic issues [72].

The challenges in the network architecture of SS in terms of spectrum sensing, decision-making and admission control were explained by [84]. The authors stated that interference occurs when SUs start their transmission whilst PU transmission is ongoing in the spectrum because of the lack of sensing accuracy. This is a serious issue in hybrid SS, especially in systems that utilise licensed bands. Moreover, propagation losses and interference occur from searching the hidden terminals of PUs and missed transmission opportunities. Software-defined research on SS design has also been conducted to reduce device-level limitations in producing inaccurate results and reducing fluctuation in signal quality [84]. Another means of alleviating the interference from the architecture perspective is to place emphasis on physical layer design in order to strengthen the spatial focusing effect from mmWave and massive MIMO. The MAC layer design will focus on how to utilise the focusing effect to accommodate more users. This will lead to other issues in the MAC layer, and re-investigation is required when the spatial focusing effect is considered [85]. The issues are admission control, handover and security. Zhang *et al.* [86] proposed a formulation for an optimisation problem with the objective of maximising users' satisfaction degree across the network. In the future, when EE is improved by employing energy harvesting technologies at secondary BSs, an issue might be encountered in terms of users' QoE due to the intermittent arrival of renewable energy. Therefore, the authors suggested that the energy status of secondary BSs must be considered during SS.

SS using spectrum allocation behaviour also has its issues. The deployments of SC will be trending in future 5G for cost-effective spectrum and energy-efficient solutions. The challenges in SCs include serious interference and high energy consumption. However, SS amongst SCs and macrocells can be explored either in inter or intra-cooperation. Yang *et al.* [87] suggested a cooperation method using cooperative capacity offload with spectrum leasing, cooperative power coordination for SC range expansion and cooperative relay using spectrum trading and virtual currency. For SS in mobile network operators, the challenges include incomplete information, economic properties and spatial efficiency [88]. EE network design is one of the 5G development issues in delivering high QoS to all PUs and SUs. As stated by [104], restricted transmission power can affect the performance of SS, especially in terms of data rate and transmission efficiency. Therefore, future research with focus on designing solutions to the high complexity and huge signalling overhead of the EDSS and UDN of SC is needed [89]. Rattaro *et al.* [89] presented a paid SS system to promote the SS concept to PUs, and the incorporation of dynamic pricing features was proposed as future advancement. However, the sensing accuracy and interference induced during the process must be solved.

For the spectrum access method, recent studies on NOMA were discussed by [100]. NOMA has several challenges, which were addressed by [102]. These challenges include the following: (1) determining the number of UEs to be served by a BS; (2) determining the UE clustering; (3) organizing the UEs within a cluster to follow the link quality measure; (4) achieving the objective of the cluster (either to prioritise individual UE performance, total cluster performance or the middle ground between them) and (5) allocating resources for UEs in a cluster. The resource allocation scheme based on the multi time-scale hierarchical model was studied by [96], who proposed to consider the fairness amongst users in each slice in future work. mmWave has a very wide spectrum, but its features raise broad questions. mmWave issues and several initial answers were discussed by [98], such as 'how the mmWave should be utilised amongst multiple operators', 'to what extent should the spectrum be shared' and 'how does the optimal SS arrangement vary with different frequency bands'. The same authors also suggested a study on characterisation for user allocation strategies in the interaction of dynamic traffic and interference, which will lead to a time-varying throughput performance. In time-varying traffic, users dynamically come and go according to statistics. In an SS system, spectrum handoff introduces extra handoff delay that has a great impact on 5G low-latency communication. Therefore, spectrum handoff probability and delay must be reduced. Another challenge in improving the learning efficiency of dynamic spectrum management implementation thus arises [97]. This includes learning the radio environment, such as learning the traffic patterns of PUs and the interference levels, for practical 5G SS systems.

B. COGNITIVE RADIO

The challenges for 5G cognitive terminals were highlighted in [79] to ensure the success of CRN in providing EE and high-speed connectivity to end users. Several key characteristics were discussed, and these included interoperability, context awareness, learning ability, self-optimisation, dynamic spectrum management, adaptive decoding and self-healing behaviour.

Novel architectures for cognitive networks that are intended to further increase spectrum efficiency also have their issues. The architecture based on D2D experiences interference when multiple D2D pairs share the same resources. In cognitive HetNets consisting of microcell and SCs, intercell interference can be reduced with cognitive capabilities for a spectrum-efficient network. However, a remarkable increase in overall energy consumption and infrastructure cost will occur after solving the capacity demand issue. The architecture that uses sleep mode techniques can solve the said problems, but an issue in the infeasibility of the techniques arises due to fluctuations in traffic demand over space, time and frequency. Another method to increase the coverage and spectrum efficiency in CRN is by enabling multi-hop communication. The solution can be implemented by providing backup channels for improving link reliability. However, the higher the number of hops is, the higher the switching delay is to the backup channels. The collaborative cognitive dynamic network architecture that was proposed to flexibly and intelligently exploit underutilised spectrum bands also has many challenges in terms of reconfigurable user equipment, economic models and security design [130].

Spectrum sensing as one of the CR elements has various techniques, as discussed in [16]. Sensing through the estimation approach estimates the interference in real data, but estimation errors can occur even with stationary radio frequency interference. On the one hand, underestimating (missed detection) or overestimating (dales alarm) interference leads to SINR degradation. On the other hand, correctly estimating radio frequency interference may degrade SINR when the bandwidth is varied from pulse to pulse [124]. Crowd sensing has elicited attention in recent years despite its issues, such as manifestation of abnormal data in crowd sensors [133], data incompleteness and inaccuracy [134], need for scalable radio-frequency spectrum monitoring, low-power and low-cost sensors [135], fading, shadowing and noise uncertainty effects [127]. The suggested future directions for the crowd sensing method include finding ways to process the spectrum, streamlining contextual data, improving the spectrum decision quality and implementing the sensing application in various possible platforms other than Android [127].

The spectrum allocation issues in methods based on graph, auction, game and carrier aggregation were elaborated in [83]. Other problems that cannot be overcome by fundamental protocols were identified in [71], and these include disproportionate and unequal spectrum utilisation caused by network entry, initialisation and hidden incumbent problem. In dynamic spectrum reservation, channel allocation for CRNs is prone to failures from the perspective of SNs, thus making users experience a less predictable QoS. Hence, challenges exist in ensuring the requirements of CR users for the reliability and availability of related services [112].

In [83], issues that are important for CR development towards 5G, such as common control channel, energy harvesting, NOMA and CR-based aeronautical communication, were addressed together with the importance of improving the spectrum and EE. The challenges in implementing cognitive NOMA as a spectrum access technique, including interference management, imperfect channel state information, EE, multi-carrier cognitive NOMA, cognitive MIMO-NOMA, relay selection/user scheduling, physical layer security and integration of FD technology, were discussed in [108]. Cognitive NOMA is a promising technique for efficient spectrum utilisation, and NOMA and CR are interference-limited. However, power domain multiplexing of NOMA causes the coexistence of inter-network interference between PNs and SNs and intra-network (co-channel) interference, resulting in the degradation of reception reliability [108]. The challenges in the exclusive use of the spectrum access trading model, viability assessment, CR-based cloud computing, security issues, optimal reservation contract design, embedding goodwill factor, alliance of sellers, mobility management, automated intelligent trading and social networking were covered in [17].

Spectrum handover based on packet-switched handover does not require spectrum sensing in the procedure, thus reducing handover interruption. However, during the spectrum handover process, the number of unavailable channels increases, and a channel must be verified to reduce the packet loss probability and bandwidth fragment ratio [71]. Synchronising all CR functions (SS, sensing, allocation, access and handover) needs efficient spectrum management functions. The challenge in managing dynamic spectra in CRN lies in integrating the said functions in many layers of a protocol stack to allow SUs to communicate reliably over the environments.

Enabling FD for CRN enhances the gain of throughput for PUs and SUs, but EE SS remains an issue. The trade-offs between EE and throughput and between EE and spectrum sensing accuracy were studied in [136], where SUs acted as FD relays for PUs. The energy consumption of SUs is greatly affected by the PUs' behaviours with constant change in their activities. Li *et al.* concluded that EE can hardly be achieved with a single and fixed choice of SS scheme [115]. In [116], FD SS for CRN was proposed from another perspective, that is, the PU-oriented method. This approach leads to the obstruction of SUs' opportunities to access the spectrum due to the self-interference of PUs. Then, the authors proposed a polarisation-based method to enhance SUs' transmission chances by using the signal waves' intrinsic property in electromagnetic field transmission. However, the polarisation learning accuracy requires further improvement.

Outage analysis for cognitive SS was studied to minimise the outage probability for users. However, only a few studies have been conducted on the outage analysis of two-way relaying networks for cellular scenarios in the presence of PU interference [129]. Hence, the overall outage probability of the SN system must be minimised by solving the relay location optimisation problem. To minimise delay whilst sharing a spectrum, [128] addressed the challenge in optimal resource allocation in outage analysis to determine the trade-off in tuning the length of decoding blocks.

For general 5G improvements, network synchronisation is recommended for future research. The efficient use of spectrum resources must be guaranteed. Potential inter-operator network synchronisation must be facilitated to avoid guard bands between operator assignments. This feature is beneficial for the efficient deployment of 5G NR networks in unpaired assignments and the alignment of uplink/downlink transmissions for slot and frame synchronisation.

VI. CONCLUSIONS

Realising a technology with the vast growth of devices connected together in a UDN sharing the same spectrum band is one of the major challenges in 5G. The urgency to address this important issue is the motivation of this study. Here, a detailed survey on SS techniques and CR technology was conducted. Recent 5G-enabling technologies, such as HetNets, SS and flexibility, massive MIMO, ultra-lean design, URLLC, convergence of access and backhaul, mMTC, mmWave and NM, were also explained. Classification of SS techniques was discussed together with the survey on SS and its techniques relevant to 5G networks. The focus, contributions and key features of each technique were highlighted. The CR technology in SS and other applications related to 5G were also reviewed. Future research directions in SS and CR were outlined together with their issues and challenges.

The main 5G development issues are related to EE and interference. Multi-user interference in dense networks is a serious issue, especially in licensed bands. Propagation losses and the interference that fluctuates in signal quality must be addressed at the hardware level. The interference of multiple D2D pairs in shared resources is another issue. The current solution can reduce the interference but at the cost of energy consumption and infrastructure. Multi-hop communication increases spectrum efficiency but has a high switching delay. Interference management is also needed for cognitive NOMA to handle inter-network interference, which degrades reception reliability. This comprehensive survey is expected to aid researchers in addressing important issues in achieving successful 5G applications.

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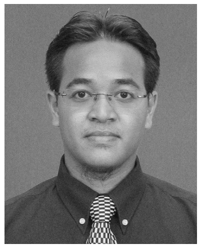

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