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Multiple Access in Cognitive Radio Networks: From Orthogonal and Non-Orthogonal to Rate-Splitting

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ABSTRACT Due to the increasingly complicated communication scenarios and network architectures as well as growing traffic demands for high speed connectivity, dynamic spectrum allocation in fifth generation (5G) networks becomes insufficient to guarantee the satisfaction of main network requirements in terms of spectrum efficiency (SE), scalability, delay, and energy efficiency (EE). Enormous multiple access schemes and cognitive radio (CR) network scenarios come to fulfill these requirements and enhance network functionalities. With multiple access schemes, users are able to transmit their data streams simultaneously under maximum capacity constraints. On the other hand, vacant spectrum holes are exploited in an opportunistic manner via CR and software defined radio. In order to exploit these spectrum holes as well as meeting different network requirements, several multiple access techniques have been presented that have been initiated through the adoption of orthogonal multiple access (OMA) scheme. Additionally, non-orthogonal multiple access (NOMA) and space division multiple access (SDMA) are presented to achieve a promising multiplexing gain as well as to address the inefficient spectrum utilization incurred with OMA schemes. However, such multiplexing gain is limited as it depend on the channel conditions. Accordingly, a generalized multiple access scheme has been presented recently, namely rate splitting multiple access (RSMA), to further enhance the SE. In this paper, we provide a comprehensive study regarding the key multiple access schemes presented for CRNs to further enhance the use of spectral resources, and additionally highlights the key implementation challenges and the enabling techniques addressed to overcome it. We have given a special attention to the enhances provided by RSMA as compared with OMA, SDMA, and NOMA techniques. Finally, some open issues are spotted to shed lights on the need for further studies and future research efforts.

INDEX TERMS Multiple access, SDMA, NOMA, RSMA, cognitive radio (CR), 5G.

I. INTRODUCTION

According to tremendous growth of the number of mobile devices and the rapid increase of wide-band and hungry data rate communication services, e.g. augmented reality (AR) and virtual reality (VR) [1], 5G networks require 1000× higher capacity, 10× higher spectral efficiency, and 100× higher connectivity density in comparison with the fourth generation (4G) [2]. Obtaining the optimal system capacity is the most challenging among 5G requirements due to shortage of spectrum resources. Of course, fixed spectrum allocation strategies can aggravate spectrum scarcity problem. As a result, it was crucial to move towards advanced spectrum management techniques, by which high spectral efficiency can be accomplished while meeting the massive connectivity requirement.

On a parallel theme, cognitive radio (CR) was introduced as a promising access solution due to its satisfactory SE [3]. The concept of CR was first introduced by the end of twentieth century [4], [5], where the secondary users (SUs) may be given the right to access the spectrum bands of the primary/licensed users (PUs) as long as the interference caused by SUs is tolerable [6]. According to study in [7], practical implementation of CR depends on opportunistic spectrum

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access, spectrum sharing, and sensing-based enhanced spectrum sharing. Without loss of generality, any multiple access scheme implies the rule of allowing many users to share the spectrum simultaneously [8] as the case with CR and hence they seeks improving SE as well as the user connectivity density.

From the first to fourth generations (1G to 4G) of mobile communications, multiple access schemes have been the Key technology that discriminates wireless systems' capacities. Orthogonal multiple access (OMA) schemes, such as frequency division multiple access (FDMA), time division multiple access (TDMA), and code division multiple access (CDMA) were used in 1G, 2G and 3G, respectively. Specifically, time, frequency and code domains are allocated fairly among active users. With 4G, orthogonal frequency division multiple access (OFDMA) has been developed for multi-user (MU) access via assigning subset of carriers for each user. The main principle of OMA techniques is separating user data steams to avoid inter-user interference and hence, achieves multiplexing gain with reasonable complexity. On the other hand, 5G SE is further challenging due to the explosive data traffic growth, caused by Wideband internet of things (WB-IoT), massive connectivity of ultra-dense Networks (UDNs), cyber physical systems, and massive machine type communications (mMTC). Orthogonal allocation approaches suffer from in-efficient distribution of available resources and inability to support massive connectivity, which push towards new access schemes as well as capacity boosting technologies such as non-orthogonal multiple access (NOMA), rate splitting multiple access (RSMA) with massive Multi-Input Multi-Output (mMIMO), ultra-dense networks and millimeter wave deployments [9]. In this comprehensive survey, we provide a special focus on NOMA and RSMA with some enabling technologies that are highly expected to enhance system capacity, spectral/energy efficiency and accommodate massive connectivity.

NOMA permits multiple users to simultaneously access the same time-frequency resource through exploiting channel gain difference which acquires allocating different power levels and/or low-density spreading codes for NOMA multiplexed users [10]. The concept behind power domain NOMA depends mainly on superposition coding of signals at the transmitter and successive interference cancellation (SIC) at the receiver [11]–[13]. While in code domain NOMA, user multiplexing can be achieved via one of the following categories: low-density spreading CDMA (LDS-CDMA) [14], [15], low-density spreading-based OFDM (LDS-OFDM) [16], sparse code multiple access (SCMA) [17], pattern division multiple access (PDMA) [18], and MU shared access (MUSA). With coded NOMA, the transmission strategy is to generate random Gaussian codes while detection follows compressive sensing to minimize symbol errors.

RSMA is a general and effective multiple access technique which comprises both of space-division multiple access (SDMA) and NOMA. Flexible architecture of RSMA tolerates with two extremes of interference management: completely treat interference as noise (as in SDMA) and completely decode interference (as in NOMA). Hence, RSMA effectively attains high throughput, variability of quality of service (QoS) and massive connectivity requirements of future multiple antenna wireless networks [19].

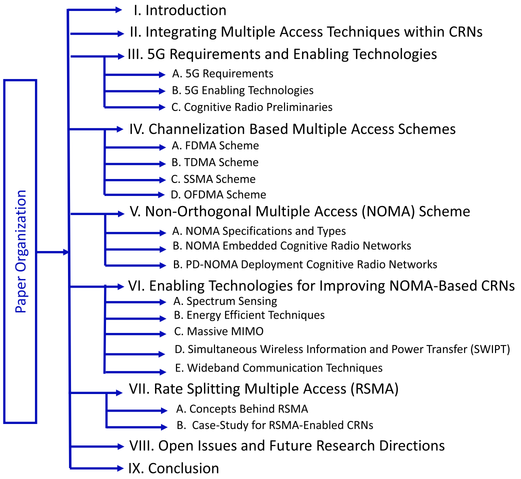


FIGURE 1. **Organization of the paper.**

The remainder of this paper is organized as follows. **Section** III presents 5G requirements and enabling techniques, preliminaries of CRNs are provided, and implementation of multiple access schemes in CRNs. Channelization based access schemes are discussed in **Section** IV while NOMA transmission protocol is demonstrated in **Section** V. In **Section** VI, we address enabling techniques for improving NOMA-enabled CRNs, then, we introduce a case-study for system model of CRN-based RSMA in **Section** VII. Finally, the conclusion is presented in **Section** VII-B. The structure of the whole paper is depicted in Fig. 1. Table 1 shows acronyms and abbreviations used in this article.

II. INTEGRATING MULTIPLE ACCESS TECHNIQUES WITHIN CRNs

One of the most important issues to be discussed regarding the dynamic spectrum allocation and sharing within CRNs is the concept of medium access control or multiple access to shared resources. The expression, multiple access schemes, refers to the approach through which multiple users or signals, either PUs or SUs or a combination of them, are combined to make the best user of the available spectral resources. Accordingly, multiple access schemes are generally used to allow for many users to share the resource simultaneously. In other words, multiple access schemes control the way through which the SUs can access the primary or licensed resource. There exist several classical multiple access approaches in the literature such as carrier sense multiple access technique and slotted ALOHA technique. However, none of these approaches suit the nature or concept of CRNs. Specifically, none of these approaches considered the concept of PUs in conventional communication networks and they did not give any consideration to the interference

TABLE 1. **Comparison between OMA and NOMA.**

	Advantages	Disadvantages
OMA	1) Low receiver complexity. 2) Less interference.	1) less spectral efficiency 2) Limited number of users. 3) Lack of users' fairness. 4) Requires synchronization 5) Limited degrees of freedoms (DoFs). 6) Large latency.
NOMA	1) High spectral efficiency. 2) Supports high connection density. 3) Sufficient user fairness. 4) Low latency. 5) Adapts with diverse QoS. 6) Compatible with other multiple access techniques.	1) Requires complex receivers. 2) High sensitivity to channel uncertainties. 3) introduces potential interference.

that may suffered at the PUs due to the existence of SUs. On the other hand, modern multiple access techniques, that have already been used to allow spectrum sharing between PUs or SUs or both, include frequency division multiple access (FDMA), time division multiple access (TDMA), space division multiple access (SDMA), orthogonal FDMA (OFDMA), spreed spectrum multiple access (SSMA), and non-orthogonal multiple access (NOMA). Accordingly, one of the principal issues that should be given full consideration when integrating multiple access techniques within CRNs is to protect the PUs and preserve its security. The multiple access techniques that could be integrated with CRNs should support the following two characteristics:

- *Avoiding the interference amongst SUs*: Since different SUs can coexist and share the resources, interference can originate if they simultaneously decide to use the same spectrum band, based on their spectrum sensing results. Thus, the multiple access scheme should coordinate the spectrum access for different SUs in order to get rid of their mutual interference. In other words, the primary user (PU) has the full right to share its band with one system/user or more systems/users. For instance, the frequency band of TV system can be shared with one or more mobile operators, and it can be shared with communication as well as radar systems. Accordingly, in such cases the PU should be responsible about regulating the use of its licensed spectrum, and modern multiple access techniques can be employed to remove or align the interference between different SUs as well as the interference from SUs on PU. The main reason behind the origination of the interference between SUs is that each SU may only be aware of the existence of PU and selfishly unaware of the existence of other SUs sharing the spectrum.
- *Interference Control and Avoidance at PUs*: This is the main requirement/condition when deciding to share the spectrum between SUs and PUs. Accordingly, the multiple access scheme should take into consideration the mode of sharing the spectrum, either spectrum overlay or spectrum underlay.

The employment of either OMA or NOMA access schemes depends mainly on the number of connections/users, SUs and PUs, and the theme of sharing the spectrum between them. OMA schemes can be employed to coordinate the shared spectrum resource while it is being accessed with multiple SUs while a controlled threshold level of interference is allowed between PUs and SUs. This scheme can be employed in cases where the number of SUs are comparable to the number of orthogonal channels. On the other hand, when the number of users is fairly greater than the number of orthogonal channels, two or more users can be allowed to access the same channel simultaneously using NOMA. Recently, CR and NOMA have been considered as vital solutions for 5G spectrum access. The Collaboration between NOMA and CR have shown a potential for improving SE, increasing system capacity, and scalability of 5G networks. The authors in [21]–[23] have illustrated that NOMA-based CRNs can achieve significant SE gains while allowing more users to be served in comparison with OMA-based counterparts. In fact, the integration of NOMA with CRNs embrace different techniques to effectively manage interference and improve energy efficiency (EE), SE, and security [10], [24]. These techniques are spectrum sensing, energy efficient massive MIMO, wireless charging mechanism, simultaneous wireless information power transfer (SWIPT) along with wide-band communication techniques such as millimeter wave, and multiband communication techniques. However, there are numerous technical challenges due to the extreme interference caused

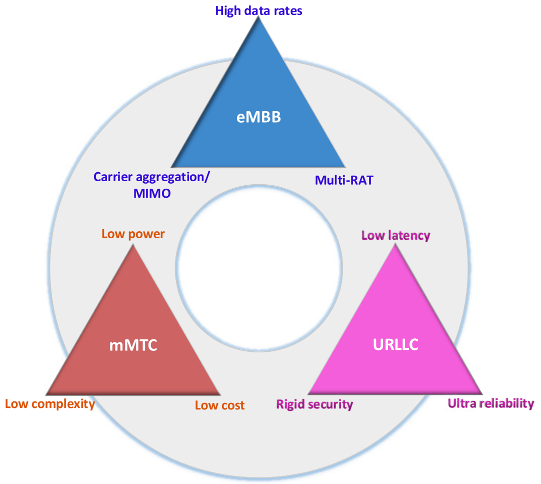


FIGURE 2. **5G services.**

by utilizing NOMA due to the fact of imperfect SIC, optimal decoding order, complexity, and likelihood propagation error as the number of users grows, and channel gain discrepancy among contributing users. Due to these limitations, numerous efforts have been made to further investigate the performance of CRs with NOMA. Moreover, the rate performance of RSMA has shown better performance compared with NOMA which makes it promising candidate for 5G network that employ CR.

III. 5G REQUIREMENTS AND ENABLING TECHNIQUES

A. 5G REQUIREMENTS

In conventional cellular networks, portable phones were practically the only type of supported devices. With the expansion of Internet and its various applications, the issue of managing several classes of traffics are investigated to meet relative QoS prerequisites for applications' varieties such as video streaming, data, VoIP calls, etc. Similarly, growing of different interconnected devices and its applications pose radical QoS prerequisites to provide superior experience to the user. Unlike previous cellular generations, 5G is envisioned to support very high density of interconnected human, machine and applications. In particular, according to international telecommunication union (ITU), a three types of services can be supported in 5G, which are mobile broadband services (eMBB), massive machine type communications(mMTC), and ultra-reliable and low latency communications (URLLC) [2], as shown in Fig. 2. This orchestration of devices and applications lead to more sophisticated network scenarios that should not only support high throughput but also provide end-to-end low latency along with low energy consumption, and high scalability for ubiquitous connectivity.

B. 5G ENABLING TECHNOLOGIES

5G network architecture is governed by a set of collaborating technologies as demonstrated by Fig. 3. The radio access will be enhanced with the deployment of wireless software-defined networking (WSDN), network function virtualization (NFV), ultra-densification, device-to-device communications (D2D), millimeter wave (mmWave), massive MIMO (mMIMO), new access techniques, Internet of Things (IoT), green communications, big data, and mobile cloud computing.

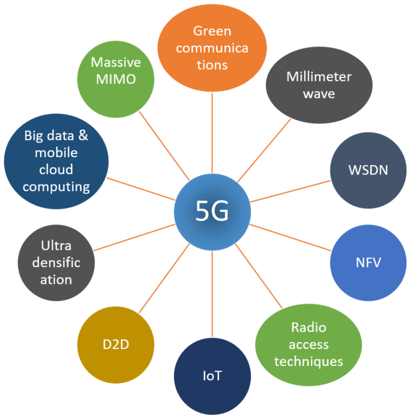


FIGURE 3. **5G technology enablers.**

Ultra-densification challenge comes from the massive growth of bandwidth demands that have been accelerated due to the development of new smartphones, tablets, wearable devices, and other new devices/ machines requiring connectivity for data roaming and/or video streaming. Two major solutions are adopted to accommodate densification, spatial densification and spectral aggregation which create virtual layers of cells and manage the shared spectrum resources wisely. In spatial densification, users are associated to different levels of cells (Macro, Micro, Femto, and Pico) to increase network capacity. While in spectral aggregation, discontiguous spectrum chunks/holes are merged together to expand the current spectrum for current applications and users [25].

Minimizing energy consumption and moving towards green communication choices are not only vital from economic perspective, but from the environmental prospective as well. The EE of cellular network can be improved by adopting optimal network planning, several combinations of network deployment strategies and harvesting renewable energy sources, which may compensate the cases of high energy consumption. For instance, CRNs have been considered as a reliable solution for minimizing energy consumption through opportunistic spectrum holes utilization with low power transmission or by harvesting energy from surroundings sources as in [26].

The aforementioned challenges and requirements motivate us to reconsider new designs for radio access. Spectral efficiency is a key factor of the radio access technique that would enable Giga bit per second (Gbps) speeds. Several 5G applications and access schemes require different criteria. For example, tactile Internet requires a very low delay in the order of 1 ms, which also limit the latency boundaries of the deployed radio access technique. Other applications such as internet of things (IoT) has a different consideration,

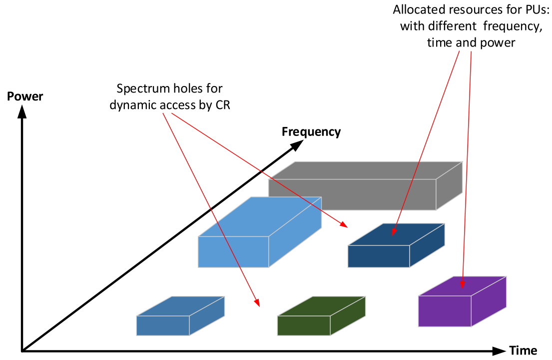


FIGURE 4. **Spectrum holes and spectrum cognition.**

wherein the devices are not connected to the BS all the time. Moreover, the power constraints of IoT devices prevent full synchronization with the BS. Hence, the adopted multiple access technique in this scenario should be able to tolerate with loose synchronization. Likewise, interference also necessitates deploying wise MU access approach. Particularly, the candidate technique should have low out-of-band (OOB) emissions, full integrity with multiple antennas and power efficient.

In this article, we will focus on multiple access techniques and its integration within CRNs in order to examine one or more of 5G requirements based on desired application.

C. COGNITIVE RADIO PRELIMINARIES

The CR is redeployed for 5G communication for the purpose of improving SE through permitting the unlicensed/ cognitive users (CU) to exploit the underutilized sub-bands which are actually allotted for the primary users (Pus) [5], [27]–[32]. CR was defined as a radio that adapt its transmission parameters according to variations in surrounding environment. From this definition, two main characteristics of CR are defined:

- **Cognitive capability:** Through real-time interaction with the radio environment, portions of the spectrum are not efficiently used at a particular time or locations as demonstrated in Fig. 4. Cognition concept empowers the usage of temporally unused spectrum, which is indicated as "spectrum hole" or "white space". Consequently, the best spectrum can be selected, shared with other users, and exploited without interfering the licensed user.
- **Reconfigurability:** CR can be programmed to transmit and receive on various frequencies while using distinctive access technologies which are supported by its hardware design [33]. Through this capability, the most excellent spectrum band and the foremost suitable operating parameters can be chosen and reconfigured.

1) SPECTRUM MANAGEMENT FRAMEWORK

The main CRNs challenge is abstracted in its coexistence with primary networks, which require considering both interference issue as well as diverse QoS requirements.

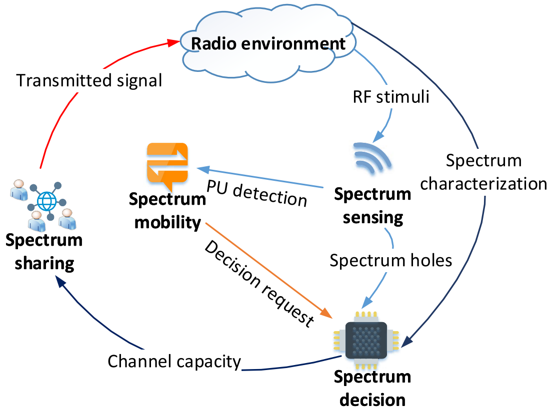


FIGURE 5. **Spectrum cognition cycle.**

To address these challenges, versatile functionalities are activated for spectrum management which called "cognitive cycle". Figure 5 shows spectrum handling through four prime steps which constitute the cognitive cycle: spectrum sensing, spectrum decision, spectrum sharing, and spectrum mobility.

- **Spectrum sensing:** is the prime function according to which the cognitive users able to monitor the available spectrum bands, capture their information, and then detect spectrum holes.
- **Spectrum decision:** Based on the spectrum availability, CR users analyze all channels and assess the most suitable channel for access.
- **Spectrum sharing:** Since there may be multiple CR users attempting to access the spectrum holes, CR coordinated access procedure to avoid collision between users' data in overlapped spectrum portions.
- **Spectrum mobility:** CR users are regarded as spectrum visitors. Hence if PU is willing to resume his services during ongoing CU data transmission, then the CU communication must be proceeded by moving it to another vacant portion of the spectrum. This process is similar or equivalent to the well-known spectrum hand-off.

2) MULTIPLE ACCESS CONCEPTS

The term multiple access schemes refer to the mechanism of combining multiple users' signals [8]. This combined signal is transmitted through a common media as shown in Fig. 6. It is additionally called multiplexing scheme. The multiple access scheme is the foremost principal of the physical layer perspective, where different crucial rules are considered for capacity enhancement. Many literature have reported that the multiple access schemes for CR systems have been overcome the growing request of extra spectrum.

3) APPLYING MULTIPLE ACCESS SCHEME TO CRN

If we assumed that we have CRN with four primary users assigned to licensed frequency band. MU access system consists of three major components: transmitter, available spectrum/medium, and receiver. Many PUs are transmitting their data frames through frequency combiner or encoder.

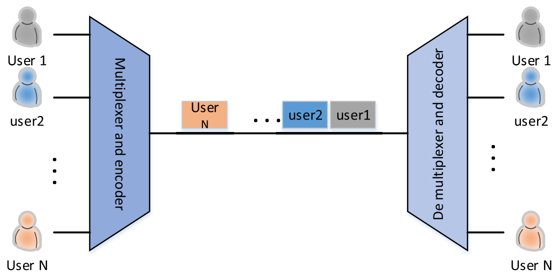


FIGURE 6. Multiple access concept.

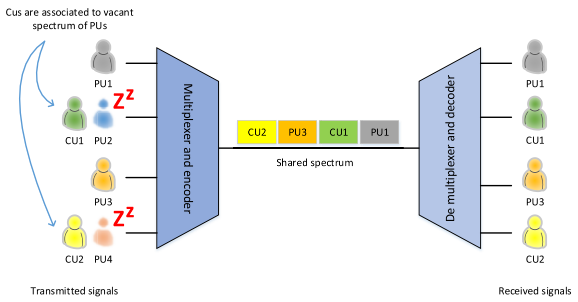


FIGURE 7. Multiple access scheme for CR network.

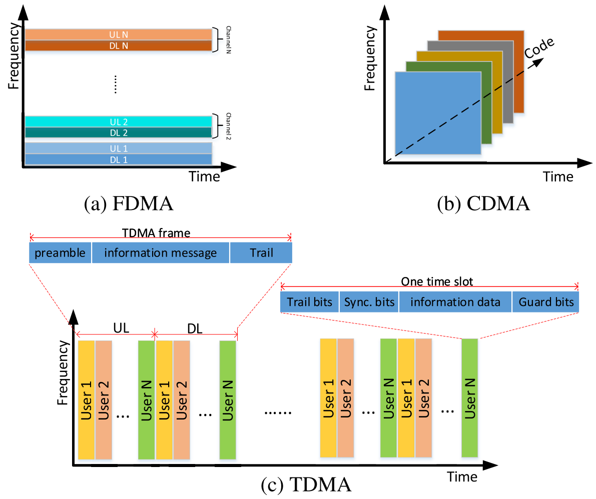
The multiplexed signal is transmitted over the medium through available spectrum. At the receiver side, the multiplexed signal is received through proper decoding. If we find after spectrum sensing process that PU2 and PU4 are in idle state. Meanwhile, arrival of any CU will be moved to vacant frequency bands of PU2 and PU4 as shown in Fig. 7. Thus, the unlicensed user can access spectrum holes opportunistically and share the same spectrum with licensed users under constraints of power and resource allocation strategy.

IV. CHANNELIZATION BASED ACCESS SCHEMES

The channelization-based schemes refer to point-to-point communication over wired or wireless channel. Each communication session possesses a partitioned channel. Five types of different access scheme based on channelization are discussed in [8], [34]. These schemes have been outlined as frequency division multiple access (FDMA) scheme, time division multiple access (TDMA) scheme, spread spectrum multiple access (SSMA) scheme, orthogonal frequency division multiple access (OFDMA) scheme and non-orthogonal multiple access (NOMA) scheme [35]. Hereafter, we briefly demonstrate the difference between these schemes.

A. FDMA SCHEME

FDMA is generally utilized in analog systems [1]. Figure 8 depicts that each user has been permanently assigned a separate frequency band, while permits for single user or single call over all time. Each user frequency band is subdivided into two sub-bands, one for sending information whereas the other employed for receiving information. These frequency bands are separated by guard band to avoid inter-user interference. This scheme was introduced in 1970s for the first generation or analog communication systems. Advanced mobile phone system (AMPS) is an illustration of FDMA deployment. The main drawback of the scheme is that when the channel isn't in use, it cannot be assigned for another user, which lead to wastage of the available resources. FDMA are used with CRN as proposed in [36], [37], wherein non-allocated channels by PUs are dynamically re-assigned to the SUs. By this way, SUs and PUs are multiplexed to enhance SE through reducing losses of frequency bands.



(a) FDMA

(b) CDMA

(c) TDMA

FIGURE 8. FDMA, TDMA, CDMA.

B. TDMA SCHEME

With TDMA, time resource is divided into time slots that equally distributed among users while the whole bandwidth remains allotted for specific user at his/her allocated time slot as appeared in Fig. 8c [8]. In particular, we have relative TDMA frames for each user spread over all frequencies. Each frame includes three parts, namely preamble, information message, and trail bits. Data is sent in the form of frames each with seven time slots which comprises user data and guard bits for minimizing inter-user interference. Consequently, TDMA performance is seven times of FDMA due to better spectrum utilization, where more than one user, with different data types, can be captured at the same bandwidth. However in narrow band communications and same conditions of transmitted power and radio environment, FDMA can achieve better coverage than TDMA.

In Europe 1990s, 2G and digital communication systems became the dominant when global system for mobile communication (GSM) was deployed via TDMA. Moreover, TDMA was also used in CRNs [38], where the authors have proposed a novel TDMA-based MAC protocol with dynamic slot allocation approach. The channels are partitioned into time slots, whereby CU send their control and data packets over their assigned slot(s). The protocol guarantees that no slot is left empty. This ensures full utilization of the available spectrum. Furthermore, the protocol ensures a reasonable sharing of available spectrum among the CUs, which reflects compatibility of TDMA with CRN.

C. SSMA SCHEME

SSMA is typically considered as multiple access scheme for 3G. It is implemented via special type of code known as Pseudo-Noise (PN) sequence, which spreads user data over all system bandwidth. There are two sorts of SSMA which are called direct-sequence code division multiple access (DS-CDMA) and frequency-hopping code division multiple access (FH-CDMA) [8], [34].

In DS-CDMA, or generally CDMA [8]; see Fig. 8b, all users share the same bandwidth via different assigned codes for each user. Randomly generated code sequences are orthogonal to each other which lead to orthogonal user allocations as TDMA and FDMA. For FH-CDMA, carrier frequencies of each user is changed via a pseudo-random hopping algorithm resides at transmitter [8]. The digital data of each user is broken into bursts with uniform sizes. Then, these bursts are transmitted over different allocated frequency bands. Without loss of generality, spreading user data has remarkable features such as immunity against multipath fading, high achievable data rates, and soft hand-off. Nevertheless, CDMA suffers from self-jamming due to near-far effect.

The spectral encoded (spread-time) CDMA (SE-CDMA) technique, which is regarded as the dual of spread spectrum CDMA, is considered for CRN as it was discussed in [39]. Once random code sequences are not fully utilized by PUs, they are powerfully allocated to CUs which in turn increases the SE. Consequently, user handles the system capacity rapidly, compared with previous multiple access schemes.

D. OFDMA SCHEME

Following orthogonalization concept, OFDMA has been selected for MU access scheme in 4G networks. OFDMA is the progressed version of MU-FDMA, whereas the guard band between adjacent sub-carriers are removed [8]. Particularly, Fig. 9 describes the orthogonality concept where users are separated from each other via non-overlapping carriers. With overlapped sub-carriers, the access approach can accommodate much more users than previous examined schemes while saving more bandwidth. Additionally, OFDMA and MU-MIMO are integrated to support versatile networks. For data burst based applications, e.g., IoT networks, OFDMA is a good candidate. Likewise, MU-MIMO and OFDMA are both used to support high bandwidth demanding scenarios. Further, OFDMA offers flexibility with CRN without extra hardware complexity [40]. The allocation of sub-carriers can be tailored according to the spectrum availability. The ease integrity with OFDM enables interoperability and accelerate the adoption of CR in future wireless systems. However, synchronization and mutual interference are the most challenging issues of OFDMA-enabled CRNs.

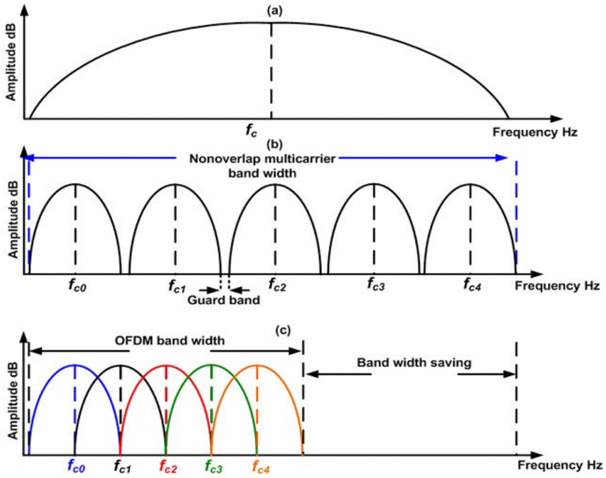


FIGURE 9. Non-overlapping multi-carrier VS orthogonal (overlapping) multi-carrier.

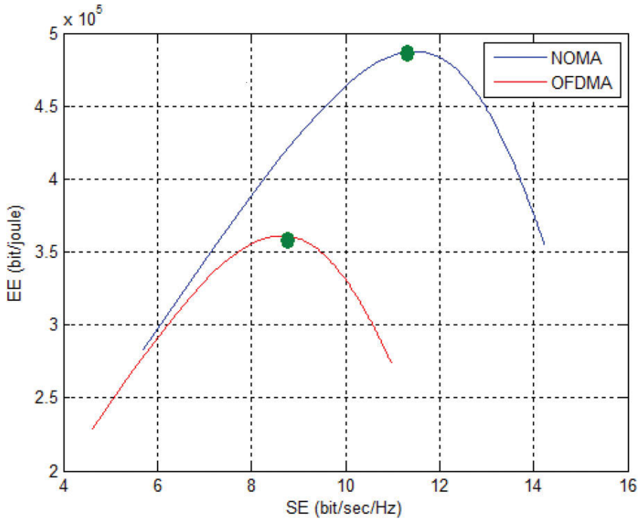


FIGURE 10. EE of NOMA VS OFDMA [42].

V. NOMA SCHEME

NOMA has been elected for radio access in 5G wireless networks [10], [35], [41]. Various researchers have demonstrated that NOMA can be used effectively to meet both network-level and user-experienced data rate requirements of 5G technologies. Furthermore, NOMA exposes higher SE and EE than the orthogonal-based access techniques [42] as shown in Fig. 10. Due to absence balancing relation between orthogonal resources and number of users, NOMA is able to support massive connectivity, whereas MUs are multiplexed at same time-frequency resource.

In [10], authors have classified the existing dominant NOMA schemes into two categories based on the non-orthogonality resources, Namely, power domain NOMA (PD-NOMA) and code domain NOMA (CD-NOMA).

A. NOMA CLASSIFICATIONS

1) PD-NOMA

With PD-NOMA, multiple users can be served in the same time and/or same frequency band via allocating different power levels per each user. NOMA depends on the principles of superposition coding at the transmitter and successive interference cancellation (SIC) at the receiver [11]–[13]. For

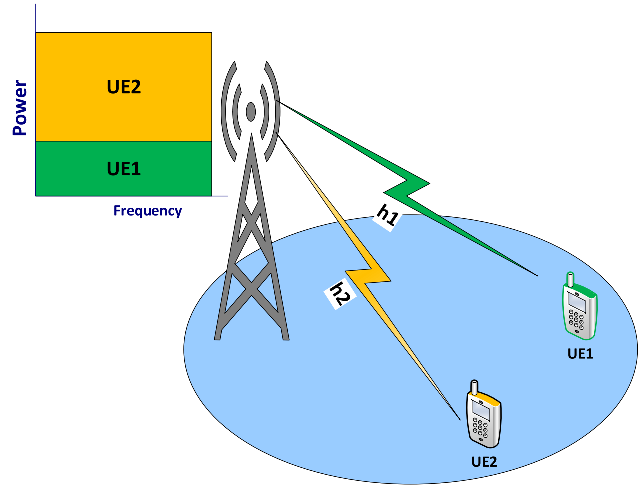


FIGURE 11. NOMA downlink transmission.

downlink NOMA [42], the base station composes the users' signals with probability of applying beamforming in case of clustered cellular network to overcome inter-cluster interference. The allocated powers for end-user creates discrepancy among NOMA users which must have different channel gains.

At strong-channel receivers, SIC is employed to detect the other users' signal and subtract it in consecutive manner to extract its own message. Figure 11 shows a base station (BS) communicating with two user equipments (UEs). In this network, it is assumed that the UE1 is the nearest one to the BS, which means $h_1 > h_2$. Particularly, UE1 employs SIC to detect UE2 first and then extract his own signal, while UE2 treats UE1' signal as noise. The optimal power allocation for downlink NOMA depends on the constraint of assigning much power for far user to compensate its channel weakness, where each user in network receives the same composite signal.

The transmitted signal by the BS can be written as:

$$X\left(t\right) = \sum_{k=1}^{2} \propto_k P_T X_k(t), \tag{1}$$

where $X_k(t)$ is the individual information of k^{th} user, $\propto_k$ is the power allocation coefficient, and P_T is the total power budget at the BS. Then, the power allocated to each user is defined as $P_k = \propto_k P_T,$, which depends on distance between user and BS. Since UE1 is the closest to the BS, lower power assigned to him compared to UE2. The received signal at k^{th} user is denoted as:

$$Y_k\left(t\right) = X\left(t\right)\ h_k + W_k(t), \tag{2}$$

where h_k is the channel gain between the BS and the UE$_k$, and $W_k(t)$ is the additive white Gaussian noise at the UE_k with zero mean and variance $N_0(W/Hz)$.

The signal of weak-channel user is decoded easily due to the sufficient power being allocated at BS. That is, the other contributing signals are regarded as interference. Therefore, the signal-to-noise ratio (SNR) for UE2 is expressed as:

$$SNR_2 = \frac{|h_2|^2\ P_2}{|h_2|^2\ P_1 + N_o W}, \tag{3}$$

where W is the transmission bandwidth. The strong-channel user, UE1, is assumed to exploit perfect SIC which result in SNR given by:

$$SNR_1 = \frac{|\ h_1\ |^2\ P_1}{N_o W}. \tag{4}$$

In general, SNR and the corresponding throughput for k^{th} user are denoted respectively as:

$$SNR_k = \frac{|h_k|^2\ P_k}{\sum_{i=1}^{k-1} |h_k|^2\ P_i + N_o W}, \tag{5}$$

and

$$R_k = W \log_2\left(1 + \frac{|h_k|^2\ P_k}{\sum_{i=1}^{k-1} |h_k|^2\ P_i + N_o W}\right). \tag{6}$$

On the other hand, with OFDMA, UEs are assigned with a group of sub-carriers, such that the total bandwidth and power are equally divided among the UEs. Hence, the throughput for each UE in this case is expressed as:

$$R_k = W_k \log_2\left(1 + \frac{|h_k|^2\ P_k}{N_o W_k}\right), \quad \forall W_k = \frac{W}{k} \tag{7}$$

2) CD-NOMA

CD-NOMA performs multiplexing in code domain. Similar to the concept of CDMA systems, The CD-NOMA shares the entire available resources of time and/or frequency via exploiting user-specific spreading sequences that are either sparse sequences or non-orthogonal cross-correlated sequences with low correlation coefficients. Coded NOMA has been divided into a few different classes as shown by Fig. 12, such as LDS-CDMA [14], [15], LDS-OFDM [16], SCMA [17], PDMA [18], and MU shared access (MUSA) [43].

LDS sequences has been used with CDMA to limit interference impact, where CDMA is primarily built upon the idea that users are separated via differences among their spreading codes. As a consequence, the chip rate of CDMA has shown much higher than the supported information data rate. In contrast, general coded NOMA scheme is able to serve multiple users through the same code. LDS-OFDM can be thought as an amalgamation of LDS-CDMA and OFDM, where the information symbols are first spread across LDS sequences and the resultant is then transmitted over set of orthogonal sub-carriers.

SCMA is a recent code-domain NOMA technique that depends on LDS-CDMA. In contrast to LDS-CDMA, the information bits can be directly mapped to different sparse

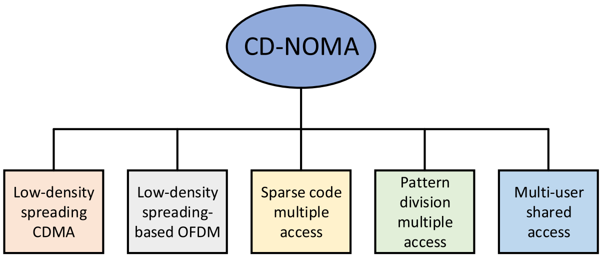


FIGURE 12. Categories of CD-NOMA.

code words where both schemes are combined. Compared with LDS-CDMA, SCMA acts as low complexity reception technique and offers improved performances.

PDMA can be realized in various domains. At the transmitter side, PDMA first maximizes the diversity and minimizes the overlaps among multiple users in order to design non-orthogonal patterns. After that, multiplexing is performed either in the code domain, spatial domain, or a combination of them.

In MUSA, multiple users' data are respectively spread by a special spreading sequences, then each user's spread data are overlapped before being transmitted. In this scheme, advanced SIC receiver is employed to demodulate and recover the data of each user at the receiving end.

Although CD-NOMA has the potential code gain to improve SE, PD-NOMA presents a simpler implementation since there is almost no modifications through the physical layer procedures at the transmitter size compared to current 4G technologies. Therefore, PD-NOMA is widely used with CRNs. To summarize the NOMA benefits, Table 1 exhibits a brief comparison between NOMA and OMA schemes.

B. NOMA-ENABLED CRNs

CR and NOMA are envisioned to be imperative solutions for 5G wireless networks. Employing NOMA techniques into CRNs has huge potential to improve SE and increase system capacity. However, there are many technical challenges due to the severe interference caused by using NOMA.

The authors in [21]–[23] have illustrated that CRNs with NOMA achieves a significant SE gains and admits larger number of users compared to OMA-based CRNs. It was shown that NOMA techniques are useful for achieving cooperation between CUs and PUs by designing appropriate cooperation mechanism for shared spectrum as in [44]–[46]. For instance, work in [44] assumes that CUs act as relays which transmit signals of both CUs and PUs depending NOMA scheme. However, this setup requires suitable channel condition. Without loss of generality, NOMA has shown better EE with CRNs than OMA-based CRNs [47]. Hereafter, we shall introduce CRNs operational schemes and their challenges with NOMA.

In CRNs, there are three operation paradigms, namely, the interweave mode, the overlay mode, and the underlay mode [7]. The underlay paradigm allows cognitive users to operate if the interference caused to non-cognitive users is below a given threshold. In overlay mode, the cognitive radios employ sophisticated signal processing and coding to maintain the communication of non-cognitive radios while obtaining some additional bandwidth for their own communication. For interweave systems, the cognitive radios opportunistically exploit spectral holes to communicate without disrupting other transmissions. The operation paradigm of NOMA-enabled CRNs allows for spectrum sharing mode between the primary network and the secondary network. Mixing one of CRN operation modes with NOMA depends on the implementation complexity, QoS requirements of PUs, and the interoperability between these two networks.

Assume we have CRNs with PD-NOMA, where the secondary network includes multiple SUs with different power levels. In the interweave mode, the frame structure consists of a sensing slots and a data transmission slots [7]. During the sensing slots, spectrum sensing is performed to detect whether the frequency bands are occupied by the PUs or not, while in the data transmission slot, the secondary network can access the free frequency bands of PUs using NOMA. Practically, spectrum sensing is imperfect due to the channel effects of shadowing and fading [3]. Therefore, false decision can be evaluated and interference constraints are considered to protect the QoS requirements of PUs. In the underlay mode, the secondary network coexists with the primary network under the condition that the interference caused by SUs is tolerable to PUs according to power allocation algorithm [48]. The authors considered power allocation for PUs according to their QoS while limiting total power of Secondary network wherein SUs are assigned with power levels relative to their channel gains.

C. PD-NOMA DEPLOYMENT FOR CRNs

Conventional PD-NOMA allocates more power to the user with poor channel conditions, which ensure user fairness. However, it cannot ensure the users' QoS targets. NOMA-enabled CR is considered as an important alternative for conventional PD-NOMA since the power allocation policy is designed such that the users' predefined QoS requirements are met. The study in [21] considered CR–NOMA, wherein BS serves two downlink users. The user with the poorer channel conditions is viewed as primary user which is assigned with much power. Moreover, the authors in [47], [49] extended the CR-NOMA systems to include multi-antennas, where it is not necessary to always treat the user with poor channel conditions as the primary user. Authors introduce more general power allocation policies for downlink and uplink NOMA scenarios which adaptively meet all users' QoS requirements.

The difference between the users' channel conditions plays vital role in NOMA design, such that users subjected to NOMA strategy must have sufficient channel gain differences. For instance, MIMO-NOMA designs depend on the fact that users have different path losses, or different channel conditions. Authors of [50] found that if the admitted users have the same pathloss, the feasibility region of NOMA rate optimization problem may become empty.

NOMA has shown a great potential to support diverse QoS requirements. The QoS requirements of NOMA-enabled heterogeneous networks might facilitate the power allocation and user scheduling strategies. In particular, users in NOMA systems are categorized according to their QoS requirements, instead of their channel conditions, which offers the two following benefits. Firstly, the SIC decoding order, power allocation, and user scheduling can be designed more appropriately to meet the users' requests. Secondly, NOMA becomes applicable for scenarios in which users channel conditions are the same.

VI. ENABLING TECHNIQUES FOR IMPROVING NOMA-ENABLED CRNs

CRNs with NOMA use different techniques to effectively manage interference and improve the EE, SE, and security [10], [24]. In the following part, we explore the main techniques that contributes in boosting NOMA-CRN performance.

A. SPECTRUM SENSING TECHNIQUES

Spectrum sensing techniques are required in the NOMA-enabled interweave CRNs to find the available frequency bands. When NOMA techniques are not applied in the primary network, the traditional spectrum sensing algorithm, e.g., energy detection, eigenvalue-based spectrum sensing, etc., can be applied. Otherwise, NOMA will provide services for multiple PUs. Although the traditional spectrum sensing algorithm is also feasible for CRN operation, the performance analysis based on independence sampling of the received signal is invalid. Accordingly, merging non-orthogonal scheme with spectrum sensing algorithms will improve spectral utilization of the future networks.

B. ENERGY-EFFICIENT TECHNIQUES

Energy-efficient techniques is divided to techniques that balance system rate along with energy consumption and these techniques which harvest energy from nature or the surrounding electromagnetic radiation. Hereafter, we demonstrate further enabling technologies which is regarded as "energy-efficient".

C. MASSIVE MIMO

Massive MIMO was applied in NOMA-CRNs where SE was significantly improved through interference management [22]. When massive MIMO is applied in NOMA-CRNs, the cognitive base station (CBS) is equipped with massive array of antennas which not only can support multiple SUs via NOMA, but also keep their transmitted powers as lower as certian threshold. Therefore, the interference caused to PUs is tolerable. Moreover, the EE can be further improved by designing energy-efficient precoding matrices for different SUs. However, many challenges should be considered such as the prior knowledge of large amount of CSI which are required to design the optimal precoding, that maximizes the capacity of the secondary network [9]. Nevertheless, it is difficult to obtain perfect CSI in practice, therefore these problems should be investigated further to find innovative techniques which help in expecting behavior of CSI such as deep learning neural networks. Moreover, CBS can provide energy supply for NOMA SUs in the downlink while receiving information from NOMA SUs in the uplink via simple structures of the CBS and SUs [9].

D. SIMULTANEOUS WIRELESS INFORMATION AND POWER TRANSFER (SWIPT)

The CBS can simultaneously transfer information and harvest energy from/to NOMA SUs with both the uplink and downlink communications. Since 5G system aims for improving SE and EE, many researchers illustrated that SWPIT is expected to provide a reasonable solution to enhance EE. It can be achieved by establishing cooperative communications protocol which combining SWIPT and NOMA, wherein cell-center users act as energy-harvesting relays to assist cell-edge users. Deploying SWIPT does not influence the diversity orders of both adjacent and far-off users compared to conventional NOMA.

Authors of [51] have designed a robust beamforming and power splitting approach for NOMA-based CRNs where they are jointly minimized the transmission power of CBS and maximizing the total harvested energy of the SUs. Minimization transmission power problem was solved under consideration of bounded and the Gaussian CSI error models for NOMA-MISO-CRN setups. Authors have also implemented a nonlinear energy harvesting model and they showed that NOMA achieves high performance gain when each user in the network can achieve a rate higher than a specific threshold.

E. WIDE-BAND COMMUNICATION TECHNIQUES

Wide-band communication techniques are expected to significantly enhance the capacity of NOMA-based CRNs. There are mainly two techniques namely, mmWave and multi-band communications.

1) mmWave COMMUNICATIONS

It operates on frequency range lies between 30 and 300 GHz as shown in Fig. 13. It is envisioned that integrating mmWave communications into NOMA-based CRNs provides ultra-wideband services and allows for massive connectivity of different devices that have diverse service requirements [52].

2) MULTI-BAND COMMUNICATIONS

It provides the potential to efficiently manage the interference between the primary network and the secondary network. It also introduces better channel maintenance by reducing hand-off frequency, and improves the flexibility of system design through allowing multiple access schemes. Hybrid multiple access mechanism combines OFDMA with NOMA which is designed to decrease the mutual interference

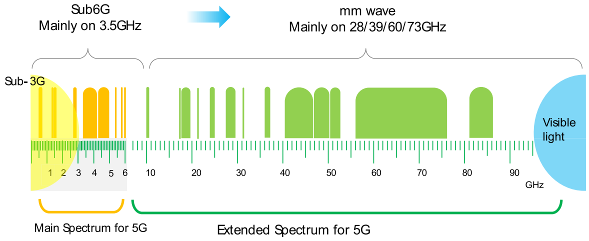


FIGURE 13. **Spectrum-sub 6G and mmWave.**

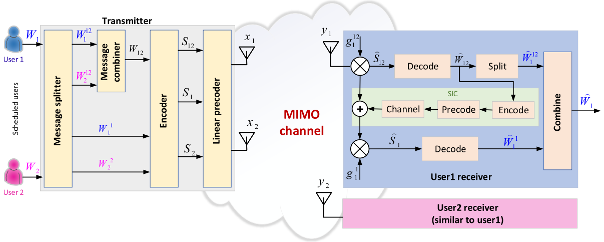


FIGURE 14. **MIMO system with two users exploiting RSMA.**

between primary and secondary networks and improve the capacity of SUs [24]. Specifically, SUs can be paired into several clusters. Users in each cluster access their spectrum using NOMA while inter-cluster interference is removed by assigning orthogonal band for each cluster.

VII. RATE SPLITTING MULTIPLE ACCESS (RSMA)

A. THE CONCEPT BEHIND RSMA

RSMA is a general and effective multiple access technique which has special forms of SDMA and NOMA. Particularly, SDMA employs linear precoding scheme to distinguish users in the spatial domain and fully depends on treating any residual multi-user interference as noise. Besides, NOMA operates on the principle of superposition coding at the transmitter and SIC at the receiver. In this setup, users are superposed in the power domain which relies on user grouping and ordering to enforce some users with better channel conditions to fully decode and cancel interference created by other users.

Conventional multiple access architectures are confined into two extremes which are defined by completely treating interference as noise (as in SDMA) or decoding interference (as in NOMA). To handle this issue, RSMA uses linear precoding rate-splitting with SIC to decode a part of the interference while the remaining part is regarded as noise. Hence, RSMA is considered as the bridge between SDMA and NOMA with low computational complexity [19].

To illustrate the concept of RSMA, consider the downlink transmission of a two-user MISO system with single BS which is equipped with N_t transmit antennas for communication with two single-antenna users. The intended users' signals are denoted by W_1 and W_2 such that each message is partitioned into two parts which are recognized as common and private streams: $\left\{W_1^{12}, W_1^1\right\}$ and $\left\{W_2^{12}, W_2^2\right\}$ for user1 and user2, respectively. Common streams $\left\{W_1^{12}, W_2^{12}\right\}$ are combined and encoded together as S_{12} via a codebook shared by both users. Later, S_{12} will be decoded by both users. The private steams, $\left\{W_1^1, W_2^1\right\}$, are encoded separately into S_1 for user1 and S_2 for user2, respectively. The overall data streams, $s = [s_{12}, s_1, s_2]^T$, are linearly precoded via precoding vector $P = [p_{12}, p_1, p_2]$ with $p_{12}, p_1, p_2 \in \mathbb{C}^{N_t \times 1}$. Therefore, the transmitted signal is expressed as: $x = p_{12}s_{12} + p_1 s_1 + p_2 s_2$, with $x \in \mathbb{C}^{N_t \times 1}$.

At user side, user1 for instance, the common stream is decoded into $\hat{W}_{12}$ by considering private steam as a noise. After that, $\hat{W}_{12}$ is post processed through SIC block to extract private steam $\hat{W}_1^1$. Finally, user receiver combines decoded steams $\hat{W}_1^1$ and $\hat{W}_1^{12}$ to reconstruct its original message as shown in Fig. 14.

Driven by the rapid development of advanced multimedia applications such as virtual reality [1], wireless networks of next-generation [53] must support high SE and massive Connectivity. By allocating different power levels, NOMA can simultaneously serve multiple users at the same frequency or time resource [10], [54]. Consequently, as we show previously NOMA-based access scheme can achieve higher SE than conventional OMA counterparts [55], [56]. With NOMA, the users must decode all of the interference as they receive the messages which significantly increases the computational complexity of corresponding signal processing. Therefore, RSMA was proposed for better EE and SE through adjusting the splitting ratio of user signal into common and private portions. Accordingly, computational complexity and the achievable data rate can be controlled.

Without loss of generality, implementing RSMA face several challenges as mentioned in [57] such as the split of common and private messages, resource management of the effective private message transmission, and synchronization of message transmission. Many papers studied these issues [57]–[60], [63]–[65]. In [57], authors introduced the challenges and opportunities of MIMO-based RSMA networks. The study in [58] proposes a distributed rate splitting method to maximize the data rate of users, while it proves that RSMA has more SE than SDMA and NOMA for wide range of users deployments as in [59]. Moreover, the system model in [59] considers diversity of channel directions, channel strengths, and in the presence of perfect and imperfect CSI at the transmitter side (CSIT). Linear precoded rate splitting method for SWIPT was investigated in [60]. The performance of EE of RSMA compared to that of NOMA was studied in [63] while considering mmWave downlink transmission scenario. In [64], the total rate of RSMA-based downlink MU-MISO systems was maximized assuming imperfect CSIT.

Authors of [19] examined the EE performance of RSMA, NOMA and SDMA, where their results proved that the EE region achieved by RSMA is always equal or larger than that achieved by SDMA and NOMA for wide range of users with diversity of channel directions and channel gains. Accordingly, RSMA ensures more SE and EE than previous mentioned multiple access schemes. In the next section, we discuss RSMA implementation with CRN as a suite for

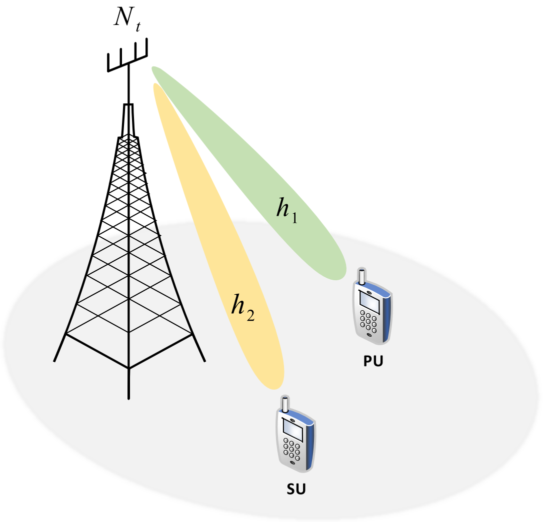


FIGURE 15. **MISO-enabled CRN.**

5G applications access. Additionally, it has been illustrated that NOMA is more suitable to single antenna settings, and it is not beneficial in most multi-antenna deployments. Moreover, RSMA as a non-orthogonal transmission framework fully exploits the multiplexing gain and the benefits of SIC to boost the rate in multi-antenna scenarios [20].

B. CASE STUDY: RSMA-ENABLED CRN

Consider downlink transmission of CRN as shown in Fig. 15, where one PU coexist with one SU and both are communicating with the same BS simultaneously. For antenna setup, we consider MISO system, where BS is equipped with N_t transmitting antennas and each user has single antenna. The mutual interfere between users' links brings constraints on the link performance and the QoS of both PU and SU. Signal-to-interference-plus-noise ratio (SINR) is regarded as a proper measure for PU and SU QoS. Since downlink is considered for PU and SU, interference from SU towards PU stems from the same location, the BS, So the channel gain from SU to PU is h_1. The channel gains from BS to PU and SU are $\mathbf{h}_1$ and $\mathbf{h}_2$, respectively, where $\mathbf{h}_{1,2} \in \mathbb{C}^{N_t \times 1}$.

The transmitted signal $\mathbf{x}$, is encoded by RSMA scheme into independent streams: common and private signals, $\mathbf{x}_p$ and $\mathbf{x}_c$, where $\mathbf{x}$ is defined as $\mathbf{x} \in \mathbb{C}^{N_t \times 1}$. The total transmitted power of the BS is limited by P_T,i.e., $\mathbb{E}\left[\|\mathbf{x}\|^2\right] \leq P_T$, the received signal at each user is represented as:

$$y_{PU} = \mathbf{h}_1^H \mathbf{x} + n_1, \qquad (8)$$

$$y_{SU} = \mathbf{h}_2^H \mathbf{x} + n_2, \qquad (9)$$

where n_1, n_2 denote the AWGN with zero mean and variance of σ^2 at the primary and secondary users, respectively.

Both PU and SU share the same codebook that is used to encode the common signal of both PU and SU. Thus, the common signals of the PU and SU are jointly encoded to form a common independent data stream e_c. On the other hand, the private signals are encoded according to precoding scheme such that PU encodes his private signal into stream e_{PU} meanwhile SU encodes his own private signal into stream e_{SU} using the beamformers $\mathbf{P}_{PU}$ and $\mathbf{P}_{SU}$. Therefore, the transmitted signal, $\mathbf{x}$, of the RSMA can be expressed as $\mathbf{x} = P_e = \mathbf{P}_c e_c + \mathbf{P}_{PU} e_{PU} + \mathbf{P}_{SU} e_{SU}$.

In order to encode the common part of PU and SU, the interference from the private signals is treated as noise. Thus, the common stream, e_c, refers to the part of the desired signal of both PU and SU, and also refers to the intended user. The SINR of the decoded common stream at the PU and SU $\text{SINR}_{c,PU}$ and $\text{SINR}_{c,SU}$ can be calculated respectively as:

$$\text{SINR}_{c,PU}(\mathbf{P}) = \frac{\left|\mathbf{h}_1^H \mathbf{P}_c\right|^2}{\left|\mathbf{h}_1^H \mathbf{P}_{PU}\right|^2 + \left|\mathbf{h}_1^H \mathbf{P}_{SU}\right|^2 + \sigma^2}, \qquad (10)$$

$$\text{SINR}_{c,SU}(\mathbf{P}) = \frac{\left|\mathbf{h}_2^H \mathbf{P}_c\right|^2}{\left|\mathbf{h}_2^H \mathbf{P}_{PU}\right|^2 + \left|\mathbf{h}_2^H \mathbf{P}_{SU}\right|^2 + \sigma^2}, \qquad (11)$$

and the corresponding achievable rates of the common signals can be evaluated by:

$$R_{c,PU}(\mathbf{P}) = W \log_2\left(1 + \text{SINR}_{c,PU}(\mathbf{P})\right), \qquad (12)$$

$$R_{c,SU}(\mathbf{P}) = W \log_2\left(1 + \text{SINR}_{c,SU}(\mathbf{P})\right). \qquad (13)$$

To ensure that the common signal is decoded by both PU and SU, the achievable rate is generally expressed as:

$$R_c\,(\mathbf{P}) = \min\left(R_{c,PU}(\mathbf{P}), R_{c,SU}(\mathbf{P})\right) \qquad (14)$$

This common achievable rate, $R_c(P)$ is shared by both PU and SU, as each user contributes with a portion of this common signal. After decoding the common signal, each user starts decoding the private data stream, e_{PU}, e_{SU}. Denote C_k as the kth user's portion of the common rate ($k = 1$ for PU user and $k2$ for SU). We have:

$$C_{PU} + C_{SU} = R_c(P)$$

After decoding the common signal, each user starts decoding its private data stream, e_{PU} and e_{SU}. Accordingly, the SINR of decoded private signals, $\text{SINR}_{p,PU}$ and $\text{SINR}_{p,SU}$, of PU and SU can be denoted respectively as:

$$\text{SINR}_{p,PU}(\mathbf{P}) = \frac{\left|\mathbf{h}_1^H \mathbf{P}_{PU}\right|^2}{\left|\mathbf{h}_1^H \mathbf{P}_{SU}\right|^2 + \sigma^2}, \qquad (15)$$

$$\text{SINR}_{p,SU}(\mathbf{P}) = \frac{\left|\mathbf{h}_2^H \mathbf{P}_{SU}\right|^2}{\left|\mathbf{h}_2^H \mathbf{P}_{PU}\right|^2 + \sigma^2}, \qquad (16)$$

and the corresponding achievable rates are evaluated as:

$$R_{p,PU}(\mathbf{P}) = W\log_2\left(1 + \text{SINR}_{p,PU}(\mathbf{P})\right), \qquad (17)$$

$$R_{p,SU}(\mathbf{P}) = W\log_2\left(1 + \text{SINR}_{p,SU}(\mathbf{P})\right). \qquad (18)$$

Therefore, the total achievable rate of PU and SU, R_{PU} and R_{SU}, can be expressed as:

$$R_{PU,tot} = C_{PU}\,(\mathbf{P}) + R_{p,PU}\,(\mathbf{P}), \qquad (19)$$

$$R_{SU,tot} = C_{SU}\,(\mathbf{P}) + R_{p,SU}\,(\mathbf{P}). \qquad (20)$$

For a given pair of weights $u = [u_1, u_2]$, put the high weight to the PU. SO the weighted sum rate (WSR) achieved by the two-user using the rate-splitting approach can be evaluated through the following optimization problem:

$$\begin{aligned} &\max_{(P,C)} R_{RSMA}(u) = u_1 R_{(PU,tot)} + u_2 R_{(SU,tot)} \\ &s.t\ C_{PU} + C_{SU} \leq R_c \\ &\quad \mathbf{tr}(PP^H) \leq P_T \\ &\quad C \geq 0 \\ &\quad R_{(}SU, tot) \geq R_{SU}^{th} \\ &\quad P_{(}SU, tot) h_1^H \leq I_{th} \end{aligned} \tag{21}$$

We assume that the total transmit power is constrained by $\mathbf{tr}(PP^H) \leq P_T$ where $C = [C_{PU} C_{SU}]$ is the common-rate vector required to be optimized with the beamforming vectors in order to maximize the WSR. The $C_{PU} + C_{SU} \leq R_c$ constraint ensures that the common stream can be successfully decoded at both users. The $R_{(SU,tot)} \geq R_{SU}^{th}$ constraint to ensure the QoS of SU, the sum rate is greater than a specific threshold. If the maximum interference level tolerable by the PU is denoted by I_{th}, the corresponding interference constraint can be expressed as $P_{(SU,tot)} h_1^H \leq I_{th}$, where $P_{(SU,tot)} = [P_C P_{SU}]$ power vector of SU.

The optimization problem in (21) can be considered as an answer to the question of ''How to model the integration of the concepts of cognitive radio and RSMA?'' mathematically. This optimization problem is just a proof of concept; however, it could be modified according to the scenario and the objective of the problem. We provided the problem without solution to give the reader the opportunity to study the same problem under different constraints and objectives. By doing this, we are trying to generalize the concepts and the optimizations to open new issues and directions. However, it is not so difficult to provide a solution to the problem provided in (21), which represents the standard form of the weighted minimum mean square error optimization problem, where a detailed study for such approach in similar problem is already provided in [65]. Another possible solution to such optimization problem can be divided to two steps. **First**, convert the non-convex problem into bi-level programming where the upper optimization problem that obtain the approximately optimal k^{th} user's portion of the common rates is solved by using particle swarm optimization. **Second**, solve the inner optimization problem that obtain precoding vectors based on a semi-definite relaxation method or a successive interference cancellation method inspired by solution in [62].

VIII. OPEN ISSUES AND FUTURE RESEARCH DIRECTIONS

In this paper, we have studied different multiple access techniques that have been introduced for improving the SE, EE, and help in making massive connectivity a feasible strategy while taking care of the encountered interference. Then, a special interest is given to the deployment of RSMA in CRNs. It has been demonstrated that RSMA is a powerful multiple access scheme that can achieve higher data rates and reliable communications in CRNs, compared to legacy OMA and NOMA counterparts. However, several important issues need to be given much attention in terms of analysis and study before the practical implementation of RSMA in CRNs. In the following subsections, we will briefly mentioned the most important issues that can be considered as an open issues for future research in the area of integrating RSMA and CRNs.

A. JOINT OPTIMIZATION OF CRNs AND RSMA PARAMETERS

CRNs have been proposed as a solution to spectrum scarcity problem through sharing the spectral resources between multiple systems/users. While sharing the spectrum, mutual interference is generated between SUs and PUs. This mutual interference is of course a function of the rate splitting parameters or the power allocation factors in the RSMA-based system. Accordingly, there should be a joint optimization problem for both the RSMA parameters such as rate splitting, power allocation, beamforming design, and the design of common messages as well as the CRNs parameters that are related to the spectrum sharing between SUs and PUs. Moreover, in CRNs with dynamic environments where both PUs and SUs are in continuous movement, joint optimization of CRNs and RSMA parameters would achieve much higher SE and EE, with respect to conventional OMA and NOMA based CRNs. These optimization problems are typically NP-hard, non-convex, and non-linear which in turn may leads to complex solutions. These solutions may rely on different optimization approaches such as successive convex approximation, mixed-integer non-linear problem solving approaches, and alternating optimization. However, there are some systematic mathematical relaxations for such kind of problems, but it is still suffer some complexity issues. We propose leveraging some machine learning tools to provide solutions with much less complexity. It is expected that artificial intelligence, specifically machine learning tools, will maintain a smart trade-off between accuracy and complexity with the availability of extra higher computational requirements.

B. SPECTRUM SENSING APPROACHES FOR RSMA-AIDED CRNs

RSMA-aided CRNs deployed within the 5G and beyond networks of course would need much intelligent spectrum sensing algorithms. The new sensing algorithms should take into account the new network architectures, new services and scenarios, and the need to integrate different kinds of wireless networks, i.e., such as communication and radar sensing networks. In our opinion, the new sensing algorithms can provide excellent solutions and greatly enhance the network performance if machine learning approaches are employed and inputted by information about the traffic models, networks architectures, highly dynamic environments, PUs and SUs history of activities. The future spectrum sensing approaches should take into account the possibility of sharing a specific channel by more than one user based on NOMA and RSMA approaches. most of the traditional spectrum sensing approaches are based on energy detection test, which simply decide whether the power level is high or lower than a specific threshold. Future spectrum sensing schemes with NOMA and RSMA should enable multi-level power threshold as well as user identification schemes in order to scope with NOMA and RSMA-based CRNs.

C. PHYSICAL LAYER SECURITY ISSUES IN RSMA-BASED CRNs

The concept of CRNs is mainly based on sharing PU resources that maybe under-utilized with SUs such that keeping its QoS. Another main condition for CRNs is keeping security of both PUs and SUs data. The interest in physical layer security grows increasingly in the last few years, especially with the lunching of 5G systems with its massive connectivity scenarios. Accordingly, a growing interest appeared focusing on the prevention of different kinds of attackers such as man-in-the-middle and denial-of-service attacks. In our opinion, the leveraging of blockchain technology to secure the data of PUs and SUs would be an interesting point of research in the near future and should be given much attention.

D. PHYSICAL AND LOWER MEDIUM ACCESS CONTROL LAYERS FOR RSMA-BASED CRNs

RSMA would have significant impact on different activities related to physical layer and lower medium access control layers of CRNs. Specifically, the deployment of RSMA will directly impact the transmission modes, channel feedback mechanisms, user pairing, massive MIMO receiver implementations, multi-carrier transmissions and waveform shaping, SE and EE trade-off, interference mitigation, and superposition coding. So, it is of great importance to consider designing physical layer mechanisms that suits the characteristics of RSMA-enabled CRNs. The impact of different RSMA parameters on all physical layer mechanisms should be fully explored and the dynamic range of operation for different receiver components should also be specified. Special attention should be given to the issues of SE and EE which are fundamental requirements of the 5G and beyond network with special emphasis to be given to the CRNs.

IX. CONCLUSION

In this paper, we have focused on multiple access techniques and its integration with CRNs to achieve one or more 5G requirement according to the desired application. First, we mentioned the requirements of achieving high SE, high EE, and massive connectivity. These requirements are accomplished by CR technologies which have spectrum access flexibility to use unutilized frequency bands. We introduce overview in the CR systems and its functionalities through detailed survey about multiple access schemes features. To this end, the challenges raised due to implementation of different access schemes with CR are exposed. Moreover, we have discussed the promising multiple access schemes for CRNs such as NOMA and the enabling techniques to improve its performances while considering their corresponding challenges. This leads us to the new RSMA scheme that overcomes the limitations of NOMA and gives better performance in terms of energy and SE. Finally, we have investigated a case study for exploiting RSMA in CRNs, wherein the SINR performance is discussed in details.

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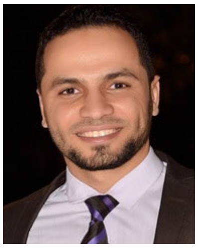

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