State of the Art, Taxonomy, and Open Issues on NOMA in Cognitive Radios

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Abstract

The explosive growth of mobile devices and the rapidly increasing demand of wideband wireless services enable an urgency for advanced communication techniques that can achieve high spectrum efficiency and satisfy the massive connectivity requirement. Cognitive radio (CR) and non-orthogonal multiple access (NOMA) techniques are envisioned to be adopted in the fifth generation wireless networks. Integrating NOMA techniques into CR networks has the tremendous potential to improve spectrum efficiency and increase the number of users. However, there are many technical challenges due to the severe interference caused by using non-orthogonal resources. Many efforts have been conducted to facilitate NOMA techniques into CR networks and investigate the effect of NOMA on them. This article aims to survey the latest research efforts made to enable NOMA techniques in CR networks. A taxonomy is devised to categorize and classify the literature based on operation paradigms, enabling techniques, objectives and optimization characteristic. Moreover, the key challenges are outlined to provide guidelines for the domain researchers and designers to realize the application of NOMA techniques into CR networks. Finally, we discuss the open research issues associated with NOMA in CR networks.

Index Terms

Cognitive radio, non-orthogonal multiple access, spectrum efficiency, massive connectivity.

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I. Introduction

THE explosive increase of the wireless connectivity, as well as the emerging demand of the broadband and high-rate communication services, such as augmented reality (AR) and virtual reality (VR), and the fixed spectrum assignment policy result in the increasingly severe spectrum scarcity problem. According to the third Generation Partnership Project (3GPP), compared with the fourth generation (4G) networks, the fifth generation (5G) networks are required to achieve 1000 times higher system capacity, 10 times higher spectral efficiency (SE), and 100 times higher connectivity density [1]. Thus, it is imperative to develop advanced communication techniques that can achieve high spectrum efficiency and provide massive wireless connectivity. As a promising technique, cognitive radio (CR) has drawn significant attention in both industry and academia due to its high spectrum utilization [2]. It can enable the secondary network (or called unlicensed network) to access the licensed spectrum bands of the primary network by using an adaptive transmission strategy in order to protect the quality of service (QoS) of the primary one.

Besides CR, non-orthogonal multiple access (NOMA) techniques have been recognized as promising techniques that can improve the SE and user connectivity density [3], [4]. Unlike the conventional orthogonal multiple access (OMA) techniques, NOMA techniques allow multiple users simultaneously access network at the same time and same frequency by using non-orthogonal resources, such as different power levels or low-density spreading codes. In [4], authors have divided the existing dominant NOMA schemes into two categories based on the non-orthogonality resources, namely, power-domain NOMA and code-domain NOMA. The pros and cons of different NOMA schemes have been comprehensively discussed and the applied situations have been characterized in [4]. The non-orthogonality enables NOMA techniques to have advantages in SE, massive connectivity, and low transmission latency at the cost of the mutual interference. In order to address the interference and decrease the implementation complexity of the receiver, multi-users detection techniques and user-pairing techniques are required [5].

It is envisioned that the integrating NOMA techniques into CR networks (CRNs) has the potential to further improve the SE and increase the number of users. However, to make it available and widely adoptable, there are several challenges required to be tackled. For example, the mutual interference between the primary network and the secondary network may be severer due to the non-orthogonal resource, and even decrease the SE. Although CR and NOMA have been extensively and individually researched, there is not much relevant work on NOMA in CRNs. The research on the integration of CR with NOMA is in its infancy. Thus, it is of great importance to understand the challenges and the benefits of this amalgamation. To this end, we conduct the study.

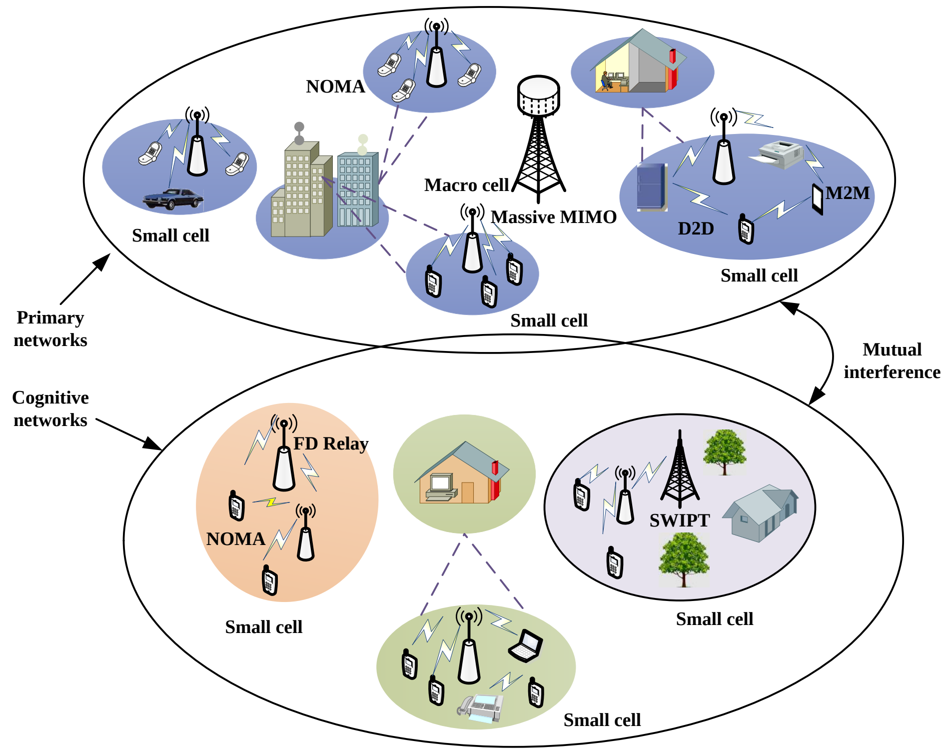

Fig. 1. Illustration of CR networks with NOMA.

The contributions of our work are summarized as follows. Firstly, we investigate, categorize and review the state-of-art research efforts made in the domain of integrating NOMA techniques into CRNs. Secondly, a taxonomy is devised based on the conducted survey considering operation paradigms, enabling techniques, objectives and optimization characteristic. Finally, we clarify the challenges and discuss the open issues as the future research directions.

The rest of the article is organized as follows. Section II presents the state-of-the-art studies on NOMA in CRNs. Then, in Section III, we discuss the devised taxonomy of CRNs with NOMA. The challenges and the open research issues are discussed in Section IV. Finally, Section VI concludes the paper.

II. State of The Art

In this section, we present the state-of-the-art research efforts made in the domain of CRNs with NOMA based on the used communication techniques and operation paradigms. Fig. 1 provides an illustration of CRNs with NOMA. It is envisioned that in order to cater to diverse service requirements, different applications, and cells with different scales, and also to efficiently manage the mutual interference between the primary network and the secondary network, multiple advanced communication techniques

Reference	System model	Resource optimization	Operation mechanism
[6]	SISO CR with NOMA	×	Underlay
[7], [8]	MIMO CR with NOMA	×	Underlay
[9]	Large-scale CR with NOMA	×	Underlay
[10]	Cooperative CR with NOMA	×	Overlay
[11]	Cooperative multicast CR with NOMA	×	Overlay
[12]	Cooperative CR with NOMA and STBC	×	Overlay
[13]	MISO CR with NOMA	√	Underlay
[14]	SISO CR with NOMA	√	Underlay

Fig. 2. Comparison of communication techniques and operation paradigms used in CRNs with NOMA.

and different multiple access techniques will be exploited, e.g., massive multiple-input multiple-output (MIMO) and full-duplex (FD) communication for achieving high SE and EE, wireless charging and simultaneous wireless information and power transfer (SWIPT) for enjoying long-time services, device-to-device (D2D) and machine-to-machine (M2M) communication for low latency and high capacity, etc. Fig. 2 presents the overview of the state-of-the-art investigations on CRNs with NOMA. The research has been conducted for three years, and an increasing attention is being drawn.

A. Performance Analysis

In CRNs, there are three operation paradigms, namely, the interweave mode, the overlay mode and the underlay mode. Fig. 3 illustrates three operation paradigms in CRNs with power-domain NOMA, where the secondary network provides service for multiple secondary users (SUs) with different power levels. In the interweave mode, spectrum sensing is required to detect whether the spectrum bands are occupied by the primary users (PUs) or not. SUs can access spectrum bands of PUs only when PUs are inactive. Regarding the overlay mode, the secondary network provides a cooperation for the primary network in order to obtain the chance to access the spectrum. In the underlay mode, the secondary network coexists with the primary network on the condition that the interference caused by SUs is tolerable to PUs (e.g., the interference temperature is tolerable). Up to now, most of the researches on CRNs with NOMA are conducted under the underlay mode (e.g., [6]-[9]) and the overlay mode (e.g., [10]-[12]). To the authors' best knowledge, there is no work on CRNs with NOMA under the interweave mode.

In [6], the authors first introduced power-domain NOMA techniques into the underlay CRNs. Under the constraint on guaranteeing the quality of service (QoS) the PU, the SU coexists with the PU by using power-domain NOMA where the SU and the PU transmit information at the same spectrum band and

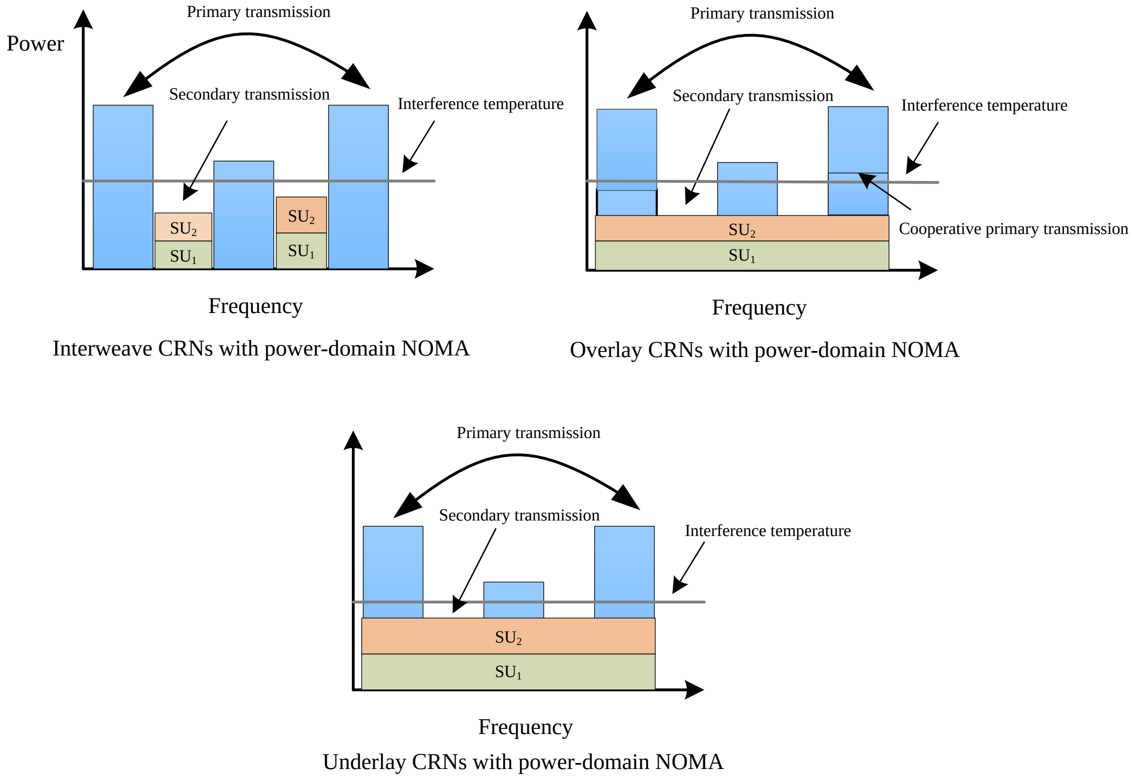

Fig. 3. CRNs with power-domain NOMA: three operation paradigms.

the same time with different power levels. Moreover, authors have investigated the impact of user pairing on the performance of CRNs with power-domain NOMA. It was shown that CRNs can achieve a good performance by using the user-pairing strategy that two users with the best channel conditions are selected to pair. It is different from the pairing strategy in conventional wireless networks with power-domain NOMA that selects the user with the best channel condition and the the user with the worst channel condition to pair.

To enhance the performance gains of NOMA, the application of MIMO techniques to CRNs with power-domain NOMA was investigated under the underlay mode [7], [8]. The impacts of the power allocation strategy based on CR and user pairing on the performance were analyzed. It was shown that the performance of CRNs with NOMA can be greatly improved by using MIMO techniques. In [9], authors have studied the performance achieved by using different power allocation strategies in large-scale underlay CRNs with NOMA. It obtained the conclusion that NOMA can outperform the conventional OMA in underlay CRNs when the target data rate and the power allocation coefficients were properly designed. The works in [6]-[9] have established the basis for the future research related to the application of power-domain NOMA into underlay CRNs.

Under the overlay mode, [10]-[12] have analyzed the performance of the application of NOMA in different CRNs. In [10], L. Lv *et al.* designed a cooperative transmission scheme based on NOMA for overlay CRNs. The aim of the proposed scheme was to allow the SU to access the spectrum of the PU and simulatively provide a cooperation for the PU. Moreover, the authors have qualitatively analyzed how NOMA techniques can be beneficial to both the PU and the SU. Furthermore, simulation results have revealed that the overlay CRNs can achieve performance gains by using NOMA techniques compared with that by using the conventional OMA techniques. Authors in [11] extended the work to the multicast CRNs and proposed a dynamic cooperative scheme under the overlay mode. A new metric was defined to evaluate the cooperative benefits. It was shown that the performances of both the PU and the SU can be significantly improved by using the proposed cooperative scheme. In [12], a two-phase cooperative protocol was proposed based on the Alamouti space time block coded NOMA in overlay CRNs. The efficiency of the proposed protocol was verified compared with the conventional scheme based on the super positing coding with respect to the outage probability and the ergodic capacity.

B. Resource Optimization in CRNs with NOMA

The works in [6]-[12] mainly focused on analyzing the achievable performance based on the proposed strategy or the proposed protocol in CRNs with NOMA. Besides the performance analysis, resource optimization is also of great importance in CRNs with NOMA. An optimal resource allocation strategy not only can take full advantage of NOMA techniques to improve the performance of CRNs, but it can also better to protect the QoS of the PU. The design of an optimal resource allocation strategy depends on the objective and the constraints of the system.

In [13], authors proposed an efficient algorithm to optimize the EE of underlay CRNs with NOMA based on the sequential convex approximation method. The considered CRNs with NOMA are general networks which consider an arbitrary number of PUs. The simulation results have shown that NOMA techniques can achieve EE gains in underlay CR compared with OMA techniques. Authors in [14] designed an optimal power allocation strategy for the underlay CRNs with NOMA. Moreover, the characteristic of NOMA techniques was exploited to design the optimal power allocation algorithm. Furthermore, the superiority of the proposed algorithm was verified by the simulation results. To the best of authors' knowledge, the research on the resource optimization for the CRNs with NOMA is very limit. There is much work to do for the application of NOMA techniques into CRNs.

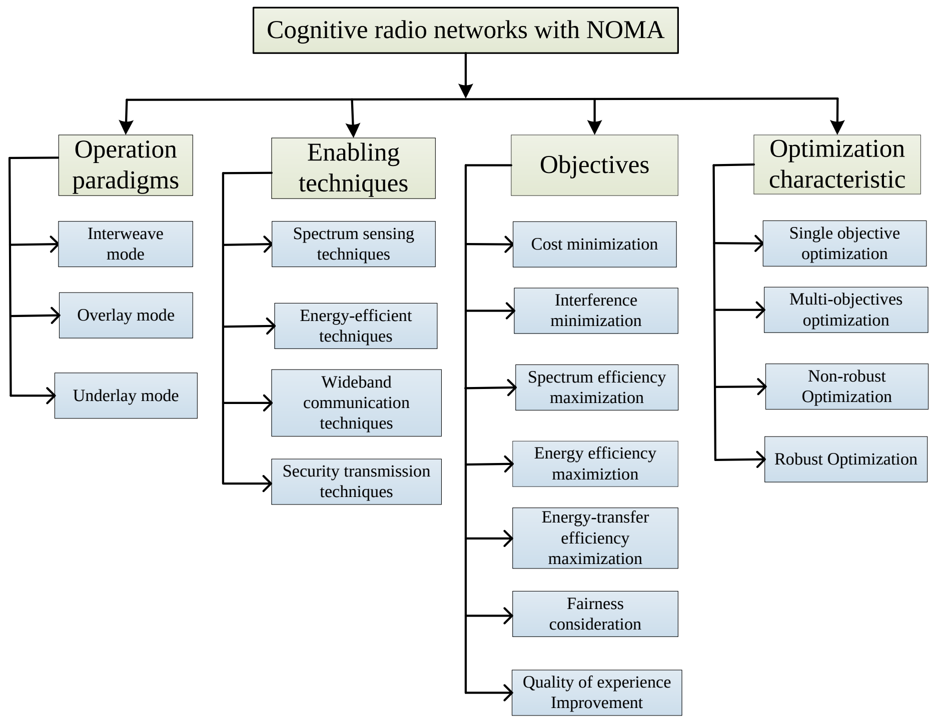

Fig. 4. Taxonomy of CRNs with NOMA.

III. Taxonomy

Fig. 4 shows the taxonomy of CRNs with NOMA. The taxonomy proposed in this article is based on the parameters, namely, the operation paradigms, the enabling techniques, objectives and the optimization characteristic.

A. Operation Paradigms

The operation paradigm of CRNs with NOMA clarifies the spectrum sharing mode between the primary network and the secondary network. The selection of the operation paradigm depends on the implementation complexity of CRNs, the QoS requirement of PUs, and the cooperative ability between the two networks. For example, the interweave mode is appropriate for spectrum bands allocated to the very high frequency/ultra high frequency (VHF/UHF) television (TV) service since the SUs can access these bands only when they are not occupied; the overlay mode can be selected when the SUs can provide cooperation for the PUs (e.g., SUs with strong channel conditions are recognized as relays to transmit PUs' information or transfer energy to PUs by using NOMA techniques in order to obtain the spectrum access opportunity); The underlay mode is a sound choice when the QoS of PUs are not high. No matter which mode is selected, the QoS of PUs should be protected, which is the precondition of CR. Although NOMA techniques have potential to improve the SE, EE and the number of users, the non-orthogonal resource may result in severe interference. Thus, spectrum sensing with a high performance is of great importance in interweave CRNs with NOMA while interference management plays a critical role in CRNs with NOMA where the overlay mode or the underlay mode is selected.

B. Enabling Techniques

CRNs with NOMA leverage various techniques to efficiently manage interference and improve the EE, SE and the secrecy in order to make full use of the spectrum and energy resource. These techniques include spectrum sensing techniques, energy-efficient techniques, wideband communication techniques and secure transmission techniques. Spectrum sensing techniques are required in the interweave CRNs with NOMA to find the available spectrum. Energy-efficient techniques aim for improving EE during the information transmission process. In order to satisfy the high capacity demand of SUs, wideband communication techniques are required. In addition, CRNs with NOMA also use secure transmission techniques to guarantee the privacy of the transmitted information.

In the interweave mode, spectrum sensing techniques with high performance are beneficial for the interference management. Up to now, many spectrum sensing algorithms have been proposed, such as energy detection, eigenvalue-based detection, cyclostationary-based detection, etc. Although these algorithms can be applied when NOMA techniques are used in the primary network, the traditional performance based on the independence assumption may be invalid due to the used non-orthogonal resource. Moreover, how to exploit the non-orthogonal characteristic to improve performances of these algorithms or develop novel algorithms is still an open issue.

Energy-efficient techniques can be divided into two categories. One is these techniques that operate in an energy-efficient way, such as massive MIMO techniques and relay techniques. The other is these techniques that can harvest energy from nature or the surrounding electromagnetic radiation, such as SWIPT techniques. In the former, the energy-efficient operation is from the space diversity and cooperation diversity. For example, when massive MIMO techniques are applied in CRNs with NOMA, the cognitive base station (CBS) equipped with a large number of antennas (e.g., more than 100) can provide serves for multiple SUs by using NOMA techniques and its transmitted power can be low so that the interference caused to PUs is tolerable. Moreover, the EE can be further improved by designing energy-efficient precoding matrixes for different SUs.

Regarding to energy harvesting (EH) techniques, there are two mechanisms, namely, the wireless charging mechanism and the SWIPT mechanism. Under the wireless charging mechanism, the CBS only provide energy supply for NOMA SUs in the downlink and forward information from NOMA SUs to the CBS in the uplink. In the second mechanism, the CBS can simulatively transmit information and transfer energy to NOMA SUs, and harvest energy from NOMA SUs and forward information from NOMA SUs to the CBS simultaneously in the uplink. The structures of CBS and SUs are relatively simple in the first mechanism whereas a higher hardware implementation complexity at CBS and SUs is required in the second mechanism. To practically realize SWIPT, the received signal needs to be split into two parts, one for harvesting energy and one for decoding information. When the SWIPT mechanism is chose in CRNs with NOMA, the hardware implementation complexity of CBS and NOMA is very high since the multiuser detection techniques and signal splitting techniques are required. In order to decrease the complexity, there are three protocols to realize signal splitting, namely, the time-domain protocol, the power-domain protocol and the antenna protocol. These protocols are designed based on the splitting domain. For example, in the time-domain protocol, the CBS and SUs switch in time between energy harvesting and information decoding.

Wideband communication techniques are expected to significantly enhance the capacity of CRNs with NOMA since a wide band is available. There are mainly two wideband communication techniques, namely, millimeter-wave (mmW) communications and multiband communications. MmW communications operate on mmWave bands between 30 and 300 GHz. It is envisioned that integrating mmW communications into CRNs with NOMA can provide a ultra-wide bands services and allow massive connectivity of different devices with diverse service requirements. For the multiband communications, it provides the potential to efficiently manage the interference between the primary network and the secondary network, obtain better channel maintenance by reducing handoff frequency and improve the flexility of system design since multiple spectrum bands can be accessed. For example, a hybrid multiple access mechanism that combines the orthogonal frequency division multiple access (OFDMA) can be designed to decrease the mutual interference between the two networks and improve the capacity of SUs.

CRNs with NOMA enables multiple SUs to access the spectrum allocated to PUs and enjoy communication services. Due to the inherent characteristics of CRNs with NOMA, malicious NOMA SUs may exist and illegitimately access the PUs' spectrum bands or change the radio environment. As a result, the legitimate SU is unable to use frequency bands of the PU or has his confidential transmitted information intercepted. Thus, secure transmission techniques are of crucial importance in CRNs with NOMA. The traditionally cryptographic techniques depend on secret keys to guarantee the communication confidentiality and increase the computational and communication overhead. It may be inappropriate in CRNs with NOMA due to the limited resource. Physical-layer security, which is based on the physical layer characteristics of the wireless channels, is a good choice to improve the security of CRNs with NOMA since it does not increase overhead.

C. Objectives

CRNs with NOMA can be deployed to improve the number of users in different situations. Based on the requirements and the available resource, the design of CRNs with NOMA has different objectives. The key objectives are cost minimization, interference minimization, SE maximization, EE maximization, energy-transfer efficiency maximization, fairness, and the improvement of quality of experience (QoE) of SUs. The cost minimization is recognized to minimize the transmission power of the CBS when it provides services for multiple SUs. The interference minimization focuses on minimizing the interference caused to PUs while considering the QoS of the SU. The objective of the SE maximization devotes to optimizing the capacity of SUs on the condition that the QoS of the PU is protected. EE is an important metric in the design of the future CRNs, which is defined as the ratio of the total capacity to the total power consumed at the CBS. The EE maximization focuses on maximize the EE of CNRs with NOMA while the SE is satisfied and the interference caused to PUs is tolerable. When energy harvesting techniques are applied in CRNs with NOMA, the energy-transfer efficiency maximization is the focus, which is defined as the ratio of the transferred power to the consumed power.

The objective of fairness tries to provide fairness among SUs while considering the different QoSs of SUs and the QoS of the PU. Up to now, several fairness criterions have been proposed, such as the max-min fairness, the proportional fairness and the harmonic fairness. The improvement of QoE is to enhance the overall acceptability of an application or service from the perspective of SUs. In order to realize the prescribed objective, resource allocation and optimization techniques are of crucial importance.

D. Optimization Characteristic

The optimization characteristic classifies the design requirement of CRNs with NOMA and the characteristic of the design objective. The single objective optimization is appropriate in CRNs with NOMA where the system design only emphasizes optimizing one performance metric (e.g., SE, EE, etc.) while other metrics can be treated as constraints of the optimization problem. In CRNs with NOMA, due to the limited resource, there exist multiple tradeoffs among various optimization objectives, such as the tradeoff between the SE and the EE, the tradeoff between the SE and the energy-transfer efficiency. However, it is difficult to achieve a good tradeoff by using the single objective optimization since it over-emphasizes the importance of one metric. Alternatively, the multi-objectives optimization can provide a good tradeoff among various conflicting objectives. Thus, it is applicable in CRNs with NOMA where multiple objectives are required to be jointly optimized.

The non-robust optimization represents these optimization problems formulated under the assumption that all the channel state information (CSI) can be perfectly obtained in CRNs with NOMA. Although the assumption is impractical, investigations on the non-robust optimization are meaningful since the results obtained under the non-robust optimization can present the theoretical limit analysis in the design of CRNs with NOMA. A robust design for CRNs with NOMA can be realized by using the robust optimization techniques. It considers the practical case that the perfect CSI in CRNs with NOMA cannot be obtained due to the presence of quantization errors, time delay and the limited feedback resource.

To solve the optimization problem in CRNs with NOMA, there are various approaches and different algorithms can be designed. These approaches can be classified as: mixed integer linear programming, convex optimization, multi-objective optimization, robust optimization and game theory. The mixed integer linear programming can be applied to solve the problem with integer variables, such as user scheduling, channel allocation, and user pairing. Convex optimization can help to solve convex problems. Regarding to multi-objective optimization, it can be exploited to obtain the Pareto optimal solution. Robust optimization can facilitate the optimization problem with infinite constraints caused by the uncertainty of CSI to transfer into the problem with finite constraints. Game theory provides a mathematical tool to model the conflict and cooperation among different objectives in CRNs with NOMA.

IV. Challenging and Future Directions

In this section, the challenges and open issues are highlighted when the enabling techniques are implemented in CRNs with NOMA. Fig. 5 summarizes the challenges and open issues.

Spectrum sensing: In interweave mode, spectrum sensing with a high performance is beneficial for the interference management in CRNs with NOMA. 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 exploited and the performance analysis is valid. When NOMA techniques are exploited to provide services for multiple PUs, although the traditional spectrum sensing algorithm can also work in CRNs with NOMA, the performance analysis based on the independence assumption may be invalid since non-orthogonal resources are used. It is challenging to derive the probability of detection when the correlation exists among samples. Up to now, how to use the correlation theory and multiple users detection theory to derive the probability of detection is an open issue. On the other hand, how to use the non-orthogonality to develop novel spectrum sensing algorithms is also an open issue.

Enabling techniques	Challenging	Open issues
Spectrum sensing	Performing performance analysis for the traditional spectrum sensing algorithms	Using the correlation theory and multiple users detection theory to derive the detection probability
	Developing novel spectrum sensing algorithms using the non-orthogonality	Spectrum sensing algorithm based on the correlation
Massive MIMO	Pilot contamination problem	Blind estimation algorithm
	Large numbers of CSI	User pairing
Energy harvesting	Energy harvesting efficiency	Different energy harvesting models
	Secure issues	Physical-layer security scheme
mmW communications	Vulnerability of shadowing	Beamforming design
	Multiple UEs access issue	New mechanisms design
Cooperative transmission	QoS requirement	Cooperative user scheduling
OMA&NOMA	The implementation complexity	User clustering
Resource allocation and optimization	Multiple objectives tradeoff	Multi-objective optimization
	Robust design	Robust optimization

Fig. 5. Challenging and open issues in CRNs with NOMA.

Massive MIMO: Massive MIMO techniques can be leveraged to significantly improve SE and efficiently manage the interference of CRNs with NOMA. However, there are two challenges to be addressed. The pilot contamination problem may be severer due to the non-orthogonal resources. Thus, it is important to design blind estimation algorithms in CRNs with NOMA. Moreover, a large number of CSI is required to design the optimal precoding for decreasing mutual interference among SUs, which is extremely difficult to obtain in practice. Thus, to practically implement massive MIMO techniques into CRNs with NOMA, there is need to design user pairing schemes to decrease the required number of CSI.

Energy harvesting: In CRNs with NOMA, there may exist energy-limited devices, such as sensors. EH techniques that leverage radio frequency signals to harvest energy are promising to extend the operated time of energy-limited devices. However, the energy harvesting efficiency (EHE) and secure issues are the two key challenges in CRNs with NOMA. The EHE depends on the harvesting circuit and the resource allocation strategy designed based on the energy harvesting model. Fig. 6 presents the existing three EH models, namely one linear EH model and two non-linear EH models [15]. The linear EH model is ideal and resource allocation strategies are relatively easy to design due to the simple energy transferred model. The non-linear EH models are practical but it is challenging to design an optimal resource allocation strategy for maximize the EHE under the two non-linear model, especially under the second non-linear model. Besides the EHE, secure issues are extremely challenging due to the open nature of CRNs and the dual function of the transmitted signal. The reason is that malicious energy-harvesting SUs may disguise themselves as licensed NOMA SUs and enjoy the service provided by CBS. How to leverage

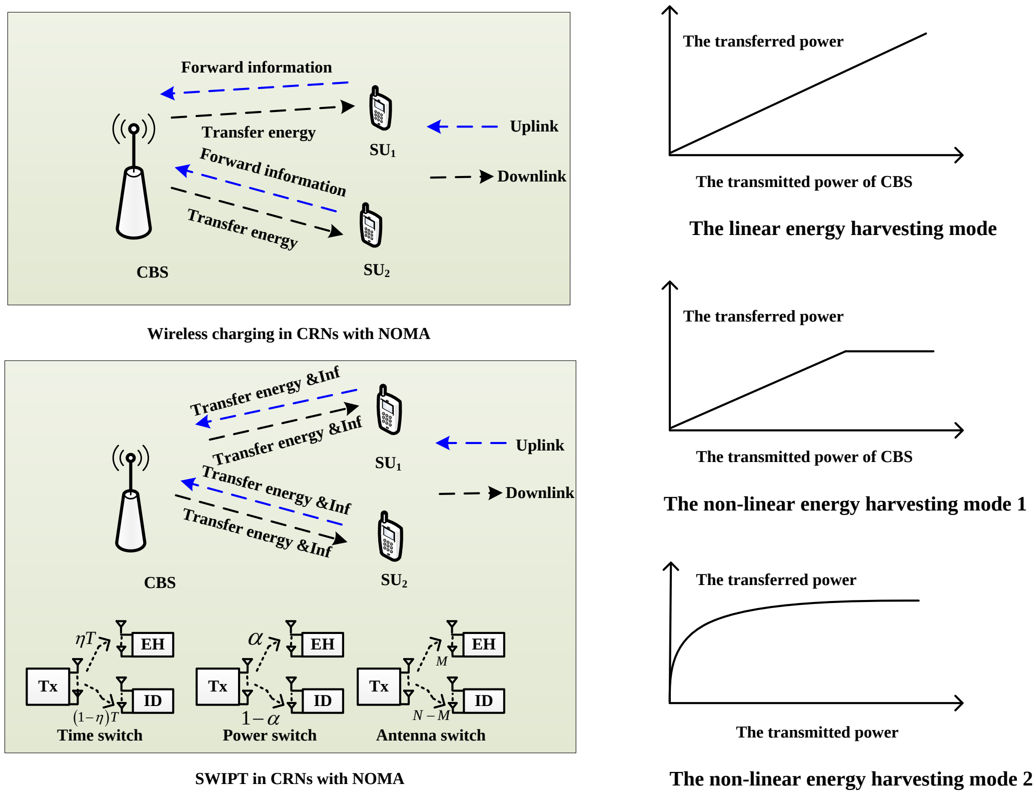

Fig. 6. Three different energy harvesting modes.

physical-layer security techniques to improve the privacy of CRNs with NOMA is an open issue.

mmW communications: Although integrating mmW communications into CRNs with NOMA has many exciting advantages, several obstacles are required to be addressed. When the primary network operates in the mmWave bands, the primary signals may suffer from the vulnerability of shadowing and the intermittent connectivity due to the ultra-high frequency. Thus, in order to protect the QoS of PUs, it is critical yet very challenging to design beamforming. Moreover, the existing investigations on mmW communications are mainly focused on point-to-point communications. How to design multiple users access mechanisms for mmW communications in CRNs with NOMA is another open issue since NOMA techniques are proposed to simultaneously serve for multiple SUs.

Cooperative transmission: In the overlay and underlay mode, NOMA SUs with strong channel condition can relay PUs' signals in order to obtain the spectrum access opportunity. In order to protect the QoS of PUs and improve the SE of CRNs with NOMA, it is crucial to select appropriate NOMA SUs as relays. Thus, how to design an optimal cooperative NOMA SUs scheduling scheme is important in CRNs with NOMA that exploits cooperative transmission techniques.

OMA&NOMA: The main challenge in implementing the hybrid multiple access in CRNs that can efficiently manage the mutual interference between the two networks and improve the SE of CRNs is the implementation complexity. If all SUs simultaneously enjoy services in the same wideband by using NOMA techniques, the implementation complexity may be extremely high, especially when there are large numbers of SUs. In order to make full use of the advantage of the hybrid multiple access, user clustering techniques need to be designed.

Resource allocation and optimization: Resource allocation and optimization are vital in CRNs with NOMA since it can not only efficiently utilize the resource, but also play an important role in the interference management. However, there are mainly two challenges to be dealt with. One is that when there are multiple conflicting objectives required to be jointly optimized, such as the EE and SE, how to design an optimal resource allocation to achieve a better tradeoff among various conflicting objectives is extremely challenging. Although multi-objective optimization can be exploited to achieve Pareto optimal solutions, the complexity of the designed algorithms may be very high. Moreover, since it is extremely difficult to obtain the perfect CSI in CRNs with NOMA, the design of robust resource allocation scheme is important yet very challenging. It needs to consider various constraints and several imperfect CSI.

V. Conclusion

The integrating NOMA techniques into CRNs has the potential to significantly improve the SE and increase the number of user connectivity. In order to enable NOMA techniques to be practically applied in CRNs, it is imperious to understand and tackle the challenges associated with it. For the purpose of understanding the challenges and realize the benefits of integrating NOMA techniques into CRNs, we conducted this work. This article firstly provided a review of the state-of-the-art research efforts made to enable NOMA techniques to implement in CR networks. Moreover, we devised a thematic taxonomy to categorize and classify the literature. Furthermore, we outlined the key challenges to enable NOMA techniques to be applied in CRNs. Finally, several open research issues in CRNs with NOMA were presented as future research directions.

We concluded that the investigation on the integrating NOMA techniques into CRNs is in its infancy. The application of NOMA techniques into CRNs has many attractive advantages, such as high SE and the ability of providing services for massive users. This application can be possible only when the presented challenges are addressed. Moreover, the discuss of the key challenges can help the domain researchers and designers to enable NOMA techniques for CR networks.

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