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Investigation on Evolving Single-Carrier NOMA Into Multi-Carrier NOMA in 5G

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ABSTRACT Non-orthogonal multiple access (NOMA) is one promising technology, which provides high system capacity, low latency, and massive connectivity, to address several challenges in the fifth-generation wireless systems. In this paper, we first reveal that the NOMA techniques have evolved from single-carrier NOMA (SC-NOMA) into multi-carrier NOMA (MC-NOMA). Then, we comprehensively investigated on the basic principles, enabling schemes and evaluations of the two most promising MC-NOMA techniques, namely sparse code multiple access (SCMA) and pattern division multiple access (PDMA). Meanwhile, we consider that the research challenges of SCMA and PDMA might be addressed with the stimulation of the advanced and matured progress in SC-NOMA. Finally, yet importantly, we investigate the emerging applications, and point out the future research trends of the MC-NOMA techniques, which could be straightforwardly inspired by the various deployments of SC-NOMA.

INDEX TERMS Non-orthogonal multiple access (NOMA), multi-carrier NOMA (MC-NOMA), power domain NOMA (PD-NOMA), sparse code multiple access (SCMA), pattern division multiple access (PDMA).

I. INTRODUCTION

THE multiple access (MA) technology not only establishes wireless connections between users and networks, but also allows users to access shared resources simultaneously in the coverage area of wireless systems. As we all know, the development of multiple access technologies reflects the evolution of wireless systems. From the first generation (1G) to the fourth generation (4G), wireless systems have utilized frequency division multiple access (FDMA), time division multiple access (TDMA), code division multiple access (CDMA), and orthogonal frequency division multiple access (OFDMA), respectively. Therefore, the signals of different users could be mapped into orthogonal resources in either the frequency domain, time domain, code domain or time-frequency domain to support multi-user access without severe inter-user interference.

As the era of the fifth generation (5G) wireless systems approaches, it is difficult for conventional orthogonal multiple access (OMA) to fulfill the requirements of the super-high data rate of user equipment (UE), ultra-low latency, ultra-reliable and massive connectivity. The non-orthogonal multiple access (NOMA) technology, which has been proven to acquire the capacity boundary of the multi-user channel, is becoming a promising candidate to meet the aforementioned requirements of 5G wireless systems. NOMA can simultaneously transmit the signals of different users at the same time-frequency resource element (RE), which is one subcarrier in one OFDMA symbol.

So far, researchers have made a few overviews and surveys on NOMA techniques, mainly focus on the research of the single-carrier NOMA (SC-NOMA). Dai *et al.* [1] present the dominant principles, key characteristics, pros and cons,

TABLE 1. **A list of abbreviations.**

Abbreviation	Description	Abbreviation	Description
1G	The first generation	MIMO	Multiple-input and multiple-output
3GPP	The third generation partnership project	ML	Maximum likelihood
4G	The fourth generation	MMSE	Minimum mean square error
5G	The fifth generation	mMTC	Massive machine type communications
AP	Access point	mmWave	Millimeter-wave
AWGN	Additive white Gaussian noise	MPA	Message passing algorithm
BER	Bit error rate	MUD	Multi-user detection
BLER	Block error rate	MUSA	Multi-user shared access
BP	Belief propagation	MUST	Multi-user superposition transmission
BS	Base station	NOMA	Non-orthogonal multiple access
CATT	China academy of telecommunication technology	OFDMA	Orthogonal frequency division multiple access
CDMA	Code division multiple access	OMA	Orthogonal multiple access
C-NOMA	Cooperative PD-NOMA	PDMA	Pattern division multiple access
C-PDMA	Cooperative PDMA	PD-NOMA	Power domain NOMA
CSI	Channel state information	QoS	Quality of service
D2D	Device-to-device	RAN	Radio access network
DCM	NTT DoCoMo Inc.	RDMA	Repetition division multiple access
DF	Decoding and forward	RE	Resource element
DL	Downlink	RI	Random interleave
EE	Energy efficiency	RIePDMA	Random interleaver enhanced PDMA
eMBB	Enhanced mobile broadband	RSMA	Resource spread multiple access
EPA	Expected propagation algorithm	SCMA	Sparse code multiple access
FDMA	Frequency division multiple access	SC-NOMA	Single-carrier NOMA
FTPA	Fractional transmit power allocation	SE	Spectral efficiency
IC	Interference cancellation	SIC	Successive interference cancellation
IDMA	Interleave division multiple access	SLS	System-level simulation
IGMA	Interleave-grid multiple access	SWIPT	Simultaneous wireless information and power transfer
KKT	Karush-Kuhn-Tucker	TDMA	Time division multiple access
LDS	Low density signature	UDN	Ultra-dense network
LDS-CDMA	Low density spreading code division multiple access	UE	User equipment
LLS	Link-level simulation	UL	Uplink
LSSA	Low code rate and signature based shared access	URLLC	Ultra reliable and low-latency communications
MA	Multiple access	WG1	Working group 1
MC-NOMA	Multi-carrier NOMA	WSMA	Welch-bound equality based spread MA

and a brief comparison of several primal NOMA techniques. In addition, the authors illustrate the opportunities, challenges, and future research trends in the design of NOMA. Besides, the authors of [2] discuss several fundamental techniques for downlink (DL) and grant-free uplink (UL) non-orthogonal transmissions, such as, multi-user superposition transmission (MUST), multi-user shared access (MUSA) and sparse code multiple access (SCMA). Furthermore, Ding *et al.* [3] introduce the concepts, challenges, latest applications and future research trends of several promising NOMA techniques. In addition, Islam *et al.* [4], [5] comprehensively represent the research status, potentials and challenges of the power-domain NOMA (PD-NOMA).

Besides, although the multi-carrier waveform is widely recognized as the vital feature in 5G, few comprehensive multi-carrier NOMA (MC-NOMA) survey has been published yet. In [3], the concept of MC-NOMA is clearly explained, and a brief introduction of various MC-NOMA techniques is given. In addition, the design principles and key features of several MC-NOMA techniques are concisely discussed in [6], from the perspective of the code-domain superposition. Yet, the most recent research progress, evaluation results and potential applications of MC-NOMA are not completely contained in these papers due to the different objects of observation.

However, there exist a lot of unique characteristics and challenges in efficiently combining MC-NOMA with the mature OFDMA that has the highest probability to be incorporated into 5G [3]. First, the theory bounds for the capacity of the MC-NOMA techniques are still inexplicit, and thus the achievable rates in different propagation environments are always evaluated by simulations. Second, efficient multi-dimensional constellations are more difficult to design and optimize than the single-dimensional power splitting. Third, the scheduling and resource allocation expanded to a much larger order of dimensions when combined with OFDMA. Fourth, the wide deployments of MC-NOMA seem more urgent, but lacking feasible applications and verifications. In one word, a comprehensive overview in the MC-NOMA research status and trends is necessary, being expected to be inspired by the fiery and explosive SC-NOMA improvement.

In this paper, we will concentrate on the inherent relation between the SC-NOMA and MC-NOMA, from the basic principles and enabling schemes. Then, we reveal the superiority of the MC-NOMA over the SC-NOMA and OMA by evaluations. Finally, we try to point out the potential research trends and applications of MC-NOMA in 5G era, which is inspired by the rapid development in SC-NOMA.

The abbreviations in this paper are listed in Table 1.

TABLE 2. Requirements and corresponding design targets of NOMA in different scenarios.

Scenarios	eMBB	mMTC	URLLC
Requirements	High capacity; high mobility; low power consumption	Massive connectivity; highly efficient small packets transmission; long-range coverage	Ultra-high reliability; ultra-low latency
Corresponding design targets	Throughput; reliability; energy efficiency	Connectivity density; coverage	Reliability; latency

A. STANDARDIZATION PROGRESS

The 3rd generation partnership project (3GPP), the authority organization of the development agencies of mobile technology specifications, has drafted several specifications on the NOMA technologies. In [7], three major 5G usage scenarios, namely enhanced mobile broadband (eMBB), massive machine type communications (mMTC), and ultra-reliable and low-latency communications (URLLC), are studied to reveal the possible implementations of NOMA. Besides, the corresponding design targets of NOMA are supplemented in [8]. Table 2 summarizes the requirements and the corresponding design targets of NOMA in different scenarios.

The 3GPP radio access network (RAN) working group 1 (WG1) officially launched a discussion on at least six potential NOMA techniques at the 3GPP RAN WG1 84bis meeting in April 2016. Huawei, ZTE, China academy of telecommunication technology (CATT), NTT DoCoMo Inc. (DCM), Qualcomm, etc., submitted more than 20 related proposals at this meeting. Subsequently, at the 3GPP RAN WG1 85 meeting in May 2016, Huawei, ZTE, and CATT supplemented the link-level simulation (LLS) results of to support the recommended MAs. Meanwhile, Samsung, LG, Fujitsu, etc. proposed their own multiple access techniques. At that time, the number of the candidate NOMA techniques increased to 12. Later, at the 3GPP RAN WG1 86 meeting in August 2016, many companies submitted the latest LLS and system-level simulation (SLS) results for the corresponding NOMA techniques, and the number of the candidate NOMA techniques increased to 15. After that, MTK, Qualcomm, etc. supplemented SLS results and actively discussed uplink grant-free communications at the 3GPP RAN WG1 86bis meeting in October 2016. Moreover, a NOMA study item for new radio was approved at 3GPP RAN 75 in March 2017, attracting attention and support from nearly 40 companies. At present, 3GPP RAN has held four workshops on NOMA, focusing on use cases, design targets, simulation assumptions, and preliminary LLS results. These workshops aim to facilitate the study phase by collecting and aligning views on various aspects from most companies. Moreover, in [9], a new NOMA technique named welch-bound equality based spread MA (WSMA) was presented at the first workshop in May 2017. Therefore, at the time of this writing, the number of the candidate NOMA techniques increases to 16.

At present, the latest research of the NOMA study item for new radio shows that NOMA techniques have their specific advantages and disadvantages to support different prospects in 5G through advanced interference cancellation (IC). Nevertheless, power domain NOMA (PD-NOMA), which has been maturely studied, could meet most requirements for deploying 5G wireless systems. Thus, it has become the most promising NOMA technique.

B. CATEGORIES OF NOMA TECHNIQUES

In order to clearly understand the 16 NOMA techniques, we make a brief classification of them. From the signature design of NOMA techniques, we can divide the existing major NOMA techniques into the original PD-NOMA and the extended NOMA. Moreover, the signature of the extended NOMA could be scrambling sequence, interleaver and spreading code. Therefore, the extended NOMA can be further classified into three categories: spreading based NOMA (SCMA, PDMA, MUSA, and so on), interleaving based NOMA (IDMA, IGMA, and RDMA) and scrambling based NOMA (RSMA and LSSA) [10]. Here, Table 3 represents the featured characteristics of all proposed NOMA techniques.

In this paper, NOMA techniques are redistricted from the perspective of the correlations in multiple REs. When the diversity of signals mapped in mutiple REs is utilized in MUD to enhance the reliability, we treat it as MC-NOMA. Typically, PD-NOMA is proposed as a single-carrier NOMA (SC-NOMA) technology, in which the UE signals mapped to different REs are uncorrelated. Though, recent studies attempt to apply PD-NOMA into the multi-carrier (MC) OFDMA systems [24]–[27]. It is believed in [3] that PD-NOMA combined with OFDMA is an extraordinary case of MC-NOMA. SCMA and pattern division multiple access (PDMA) are the two typical MC-NOMA techniques, which have been proposed at the beginning of the 5G research progress, to incorporate with the mature OFDMA technology. Meanwhile, SCMA and PDMA, which can utilize the code sparsity to reduce the system complexity, are experiencing rapid and encouraging improvements. Furthermore, SCMA and PDMA could be regarded as the evolved PD-NOMA with different superposition patterns in different REs, and they are optimized to be deployed in all the three 5G usage scenarios.

It should be pointed out that, most of the spreading based NOMA techniques could be naturally included in the scope of MC-NOMA, considering the combination with OFDMA and the spreading on multiple REs. Meanwhile, these MC-NOMA techniques are mainly proposed and promoted by the leading companies from the viewpoint of the industry, requiring further development in the theoretical bases. Thus, it is a good opportunity to learn from the advanced and explosive development in PD-NOMA.

TABLE 3. Categories of the 16 candidate new multiple access techniques.

Categories	Acronym	Affiliation	Description	Basic user differentiation	Receiver
Original NOMA	PD-NOMA [11]	DCM	Multiple UEs with different power are transmitted on the same resource	Power	Successive interference cancellation (SIC)
The spreading based NOMA	SCMA [12]	Huawei	A data stream is directly low-density spread according to a codebook	Codebook	Message passing algorithms (MPA)+IC
	PDMA [13]	CATT	Each code is used to define sparse mapping, and may have a specific diversity order	Pattern	Belief propagation (BP)
	MUSA [14]	ZTE	Use random complex spreading codes with short length	Sequence	Multi-user detection (MUD)+IC
	NOCA [15]	Nokia	Use the low correlation sequences defined in LTE as spreading codes	Sequence	Minimum mean square error (MMSE)-SIC
	NCMA [16]	LG	Spreading codes are obtained by the Grassmannian line packing problem	Sequence	MUD+IC
	LCRS [17]	Intel	Apply the direct spreading of modulation symbols to transmit the spread symbols	Sequence	Elementary signal estimator+IC
	FDS/SSMA [17]	Intel	Spread information bits with repetition and rate matching	Sequence	MUD+IC
	LDS-SVE [18]	Fujitsu	Consider user signature vector extension, transforming and concatenating signature vectors	Sequence	MPA+IC
	GOCA [19]	MTK	Use a two-stage structure to generate group orthogonal sequences and spread modulated symbols	Sequence	SIC
	WSMA [9]	Ericsson	Optimal sequences are used to achieve the Welch bound on the sum correlation of a set of vectors	Sequence	MMSE-SIC
The interleaving based NOMA	IDMA [20]	Nokia	Use specific bit level interleavers in the transmit side to separate different users	Interleaver	Elementary signal estimator+IC
	IGMA [21]	Samsung	Choose bit level interleavers and/or the grid mapping pattern to separate users	Interleaver	MPA
	RDMA [19]	MTK	Separate different user signals by utilizing both time and frequency diversity with cyclic-shift repetition	Interleaver	SIC
The scrambling based NOMA	RSMA [22]	Qualcomm	Use combination of low rate channel codes and scrambling codes with good correlation properties	Scramble	Match filter+IC
	LSSA [23]	ETRI	User data are bit-level or symbol-level multiplexed with the UE specific signature pattern	Scramble	MMSE

C. CONTRIBUTIONS AND STRUCTURE OF THIS PAPER

In this paper, we will present the above-mentioned three most promising NOMA techniques (PD-NOMA, SCMA, and PDMA). Compared with other NOMA techniques, these ones are relatively mature in the research and development. Here, we focus on the main concepts of NOMA techniques, and omit tedious explanations and mathematical derivations. The structure of this paper is represented in Fig. 1, and the main contributions of this paper are listed as follows,

- We present the basic principles and core enabling schemes of PD-NOMA, which is the original and typical SC-NOMA technique; besides, we analyze the main LLS and SLS results of PD-NOMA (Section II).
- We introduce the concepts of SCMA/PDMA, the two representative MC-NOMA techniques, and then thoroughly investigate the enabling schemes and the evaluations of SCMA/PDMA; consequently, we reveal the superiority of MC-NOMA over OMA as well as SC-NOMA, considering the combination with the dominated OFDMA waveform (Section III).
- We investigate the developed applications of SC-NOMA and the developing application of MC-NOMA, and then point out the potential research trends in MC-NOMA, inspired by the development in SC-NOMA (Section IV).

II. SC-NOMA

SC-NOMA is the primary NOMA in which user signals are superposed in a single RE. Meanwhile, PD-NOMA has been regarded as the most promising SC-NOMA scheme [3], in which uncorrelated user data are mapped into different REs and signals of different users are distinguished by their different levels of power allocation. In this section, we give a compact overview of PD-NOMA from the perspectives of basic principle, existing schemes and evaluations.

A. BASIC PRINCIPLES

PD-NOMA transmits on the same time, frequency and spatial resource by solely superposing signals of multiple users in the power domain. Then, receivers separate signals of different users by adopt advanced MUD and demodulation mechanisms. It has been proven in [28], the performance of PD-NOMA could approach the capacity boundary in uplink and downlink. As mentioned in [28]–[33], PD-NOMA uses SIC, which is differently designed in downlink and uplink, as the baseline receiver. Higuchi et al. reveal that NOMA with a SIC receiver outperforms OMA in the tradeoff of the system efficiency and user fairness, especially in the markedly different channel conditions among the users when exploiting the near-far effect [31], [32]. We assume that, one base station (BS) with a single antenna and two UEs with a single antenna are deployed in PDMA [33], and the total system transmission bandwidth is 1 Hz.

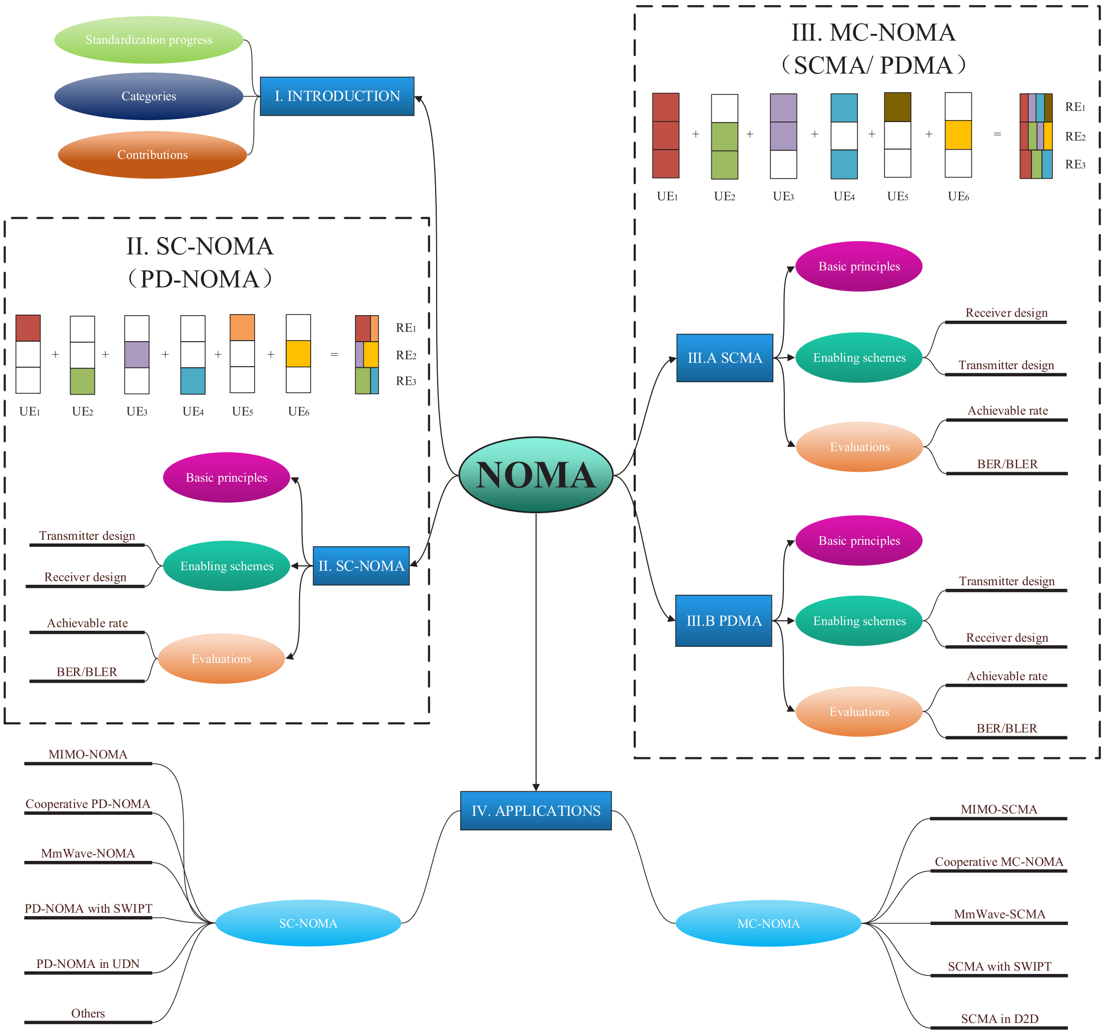

FIGURE 1. The structure of this paper.

1) DOWNLINK PD-NOMA

In downlink PD-NOMA, BS transmits the signal x_i with transmit power P_i^{DL} to $UE_i, i \in \{1, 2\}$, where $P_1^{\mathrm{DL}}+P_2^{\mathrm{DL}} \leq P$, $E[|x_i|^2] = 1$, and $E[\cdot]$ denotes the expectation function. In downlink PD-NOMA, the superposed signal of the two UEs is $x = \sqrt{P_1^{\mathrm{DL}}}x_1+\sqrt{P_2^{\mathrm{DL}}}x_2$, and the received signal at UE_i is $y_i = h_i x + n_i$, where h_i is the channel coefficient between UE_i and BS, n_i represents the additive white Gaussian noise (AWGN) with the power spectral density N_i at the receiver of UE_i.

As shown in Fig. 2, we assume that, UE_1 is the cell-center user and UE_2 is the cell-edge user, $|h_1| > |h_2|$, and UE_1 conducts SIC according to the ascending order of channel gains. Without error propagation, the achievable rates of UE_1 and UE_2 could be represented as follows

$$R_1^{\mathrm{DL}} = \log_2(1 + \frac{P_1^{\mathrm{DL}}|h_1|^2}{N_1}), \tag{1}$$

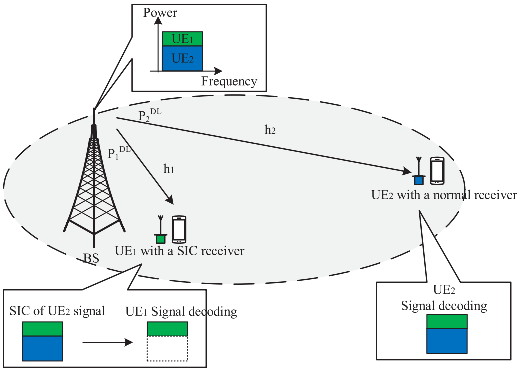

FIGURE 2. Downlink PD-NOMA with SIC applied at the receiver of the cell-center user [33].

and

$$R_2^{\mathrm{DL}} = \log_2(1 + \frac{P_2^{\mathrm{DL}}|h_2|^2}{P_1^{\mathrm{DL}}|h_2|^2 + N_2}). \tag{2}$$

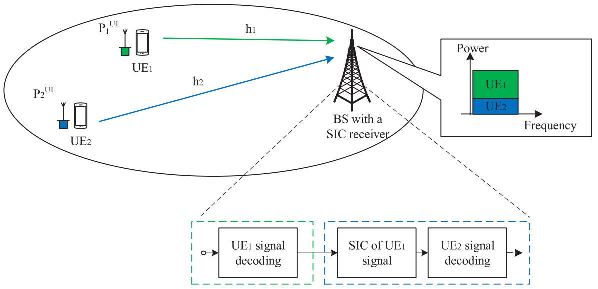

FIGURE 3. Uplink PD-NOMA with SIC applied at the receiver of BS [33].

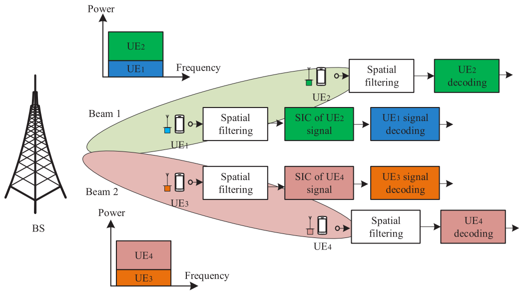

FIGURE 4. Beamforming combined with PD-NOMA [32], [34].

2) UPLINK PD-NOMA

In uplink PD-NOMA, the signal transmitted by UE_i is x_i and the transmit power is P_i, where $i \in \{1, 2\}, E[|x_i|^2] = 1$. The superposed received signals at BS is represented as $y = h_1\sqrt{P_1^{\mathrm{UL}}}x_1 + h_2\sqrt{P_2^{\mathrm{UL}}}x_2 + n_0$, where h_i is the channel coefficient between UE_i and BS, and n_0 denotes the AWGN observed at BS with the power spectral density N_0.

As shown in Fig. 3, UE_1 is the cell-center user and UE_2 is the cell-edge user, $|h_1| > |h_2|$, and BS conducts SIC according to the descending order of channel gains. Omitting error propagation, the achievable rates of UE_1 and UE_2 can be formulated as follows

$$R_1^{\mathrm{UL}} = \log_2(1 + \frac{P_1^{\mathrm{UL}}|h_1|^2}{P_2^{\mathrm{UL}}|h_2|^2 + N_0}), \tag{3}$$

and

$$R_2^{\mathrm{UL}} = \log_2(1 + \frac{P_2^{\mathrm{UL}}|h_2|^2}{N_0}). \tag{4}$$

B. ENABLING SCHEMES

1) TRANSMITTER DESIGN

a: BEAMFORMING

The beamforming technique is usually utilized with the PD-NOMA technology to form the multiple-input and multiple-output (MIMO)-NOMA system, in which non-orthogonal techniques such as superposition coding and SIC are deployed inside a beam, as shown in Fig. 4 [32], [34]. The opportunistic beamforming scheme and an enhanced one for downlink MIMO-NOMA are proposed and studied in [32], [34], and [35]. In addition, the system performance of opportunistic beamforming and enhanced opportunistic beamforming are compared in [35].

The projection hybrid PD-NOMA beamforming algorithm, combining the conventional zero-forcing beamforming and the hybrid PD-NOMA precoding, is presented in [36] to minimize interference while reducing computational complexity. Likewise, a novel multi-cluster zero-forcing beamforming method based on the precoding technique is put forward in [37] to cancel the inter-cluster interference entirely when the number of overall receive antennas is no more than the number of transmit antennas. In addition, Higuchi [32] and Nonaka *et al.* [34] propose an intra-beam superposition coding method for the cooperative downlink MIMO system by utilizing the spatial filtering to separate different beams and utilizing SIC to decode the superposed signals in a beam.

b: PRECODING

The precoding technique can be studied to utilize the spatial degrees of freedom at BS in MIMO-NOMA. A sub-optimal precoding scheme with low complexity based on singular value decomposition and an optimal precoding scheme for optimizing the sum rate of MIMO-NOMA are proposed to reach the capacity region in the MIMO broadcast channel [38]. Moreover, Chen and Dai [39] propose the minimum Euclidean distance precoding method for downlink MIMO-NOMA. In addition, the new precoding and detection matrices are put forward in [40] to enhance system performance with a fixed power allocation method while completely removing the inter-cluster interference. In brief, current precoding schemes can essentially solve the problem that the spatial degrees of freedom are not utilized efficiently in MIMO-NOMA.

c: RESOURCE ALLOCATION

Appropriate resource allocation, including user pairing and power allocation, could improve the throughput and fairness of all users in the PD-NOMA wireless system with limited resources [3], [41]. Recently, Islam *et al.* [42] discuss the open issues of the joint optimization of user paring and power allocation, and the resource allocation of MC MIMO-NOMA. In addition, they point out that low-complexity resource allocation and security-aware resource allocation are becoming future research directions. Existing resource allocation schemes are listed and compared in Table 4.

User pairing can reduce the computational complexity of executing SIC. Under the premise of guaranteeing quality of service (QoS), if there is no interference or little interference between users, all signals are transmitted on a few REs. In this way, the optimal approach is to exhaustively search over all user pairs. However, to avoid extremely high computational complexity, paper [43]–[46] propose several suboptimal user pairing schemes. Al-Abbasi and So [43] propose a vertical user pairing scheme which groups users in a pair according to the channel gains of users, where the best user and the worst user are paired each time. Thus, the number of

TABLE 4. **A Comparison of PD-NOMA resource allocation schemes.**

Reference	Objective	Scheme	DL/UL	Solution	Contribution
[26]	Energy efficiency	User pairing, power allocation	DL	Joint user pairing and power allocation optimization	Maximize overall EE with imperfect channel state information (CSI)
[41]	Fairness	Power allocation	DL	Bisection search algorithm, KKT	Optimize in instantaneous and average CSI cases
[43]	Sum rate	User pairing, power allocation	DL	Vertical user pairing, hierarchical power allocation	Resource allocation for a large number of users
[44]	Sum rate	User pairing, power allocation	DL/UL	User clustering algorithm, KKT	Maximize throughput for the users with low channel gains
[45]	Ergodic sum rate	User pairing	DL	Near user pairs two far users	Efficiently utilize the spectrum of unpaired users
[47]	Weighted sum rate	User pairing, power allocation	DL	KKT, greedy algorithm	Maximize the weighted sum rate with the optimal power allocation
[48]	Sum rate	User pairing, power allocation	DL	Greedy algorithm	Achieve resource allocation by taking into account greedy search
[49]	Sum rate	Antenna selection, user pairing	DL	Joint antenna and user contribution algorithm	Maximize the sum rate for MIMO-NOMA scenarios
[50]	Complexity	User pairing	DL	Fast proportional fairness	Pair users with the highest proportional fairness
[52]	Power	Power allocation	DL	Distributed power control	Minimize the total transmit power of BS subject to user QoS
[53], [54]	Energy efficiency	Power allocation	DL	Closed form expression	Maximize EE with a closed form expression in fading MIMO channels
[55]	Energy efficiency	User pairing, power allocation	DL	Difference of convex programming	Maximize EE of users with perfect CSI
[56]	Sum rate, outrage probability	Power allocation	DL	KKT, α-fairness, alternate optimization	Optimal power allocation with α-fairness for statistical CSI and perfect CSI at the transmitter
[57]	Maxmin fairness, sum rate, energy efficiency	Power allocation	DL	Fix one and optimize others	Optimal power allocation for different criteria
[58]	QoS,outage probability	Power allocation	DL	Fixed-power allocation	Average outage events at each user for all received signals
[59]	QoS	Power allocation	DL/UL	D-NOMA	Dynamically fulfill the requirements of various service quality
[60]	Effective capacity	Power allocation	DL	Truncated channel inversion power control	Guarantee delay QoS for two users
[61]	Power	Power allocation	DL	Fixed-point update power allocation	Give receive detection vectors
[62]	Fairness	User pairing, power Allocation	DL	user pair power allocation scheme	Guarantee efficiency and user fairness
[63]	Power	Power allocation	UL	Based on game theory	Give Pareto optimum power levels through game theory
[64]	Power	Power allocation	DL	Iterative algorithm	Eliminate the effects of mutual interference by the iterative algorithm
[65]	Fairness	User pairing, power allocation	DL	Joint user pairing and power allocation optimization	Optimal resource allocation for multi-cell scenarios

users in a pair is two. Paper [43] and [44] propose a user pairing scheme, in which the number of users in a pair can be three and four. In [45], when the number of cell-edge users is greater than the number of cell-center users, a cell-center user is proposed to pair one or more cell-edge users. Paper [47] and [48] propose the user pairing scheme based on the greedy algorithm. Besides, paper [49] proposes a joint antenna selection and user pairing algorithm. In addition, [50] proposes a fast proportional fair user pairing scheme, which pairs users according to the maximum proportional fairness index.

Since the users with weaker channel conditions may have an impact on overall system outage, allocating more power to the weaker users increases the effective channel gain and minimizes interference. Fractional transmit power allocation (FTPA) allocates power according to the reciprocal ratio of the user channel gain [51]. In addition, [52] proposes three modified FTPA power allocation schemes based on minimum SNR, average SNR, and maximum SNR. According to the Karush-Kuhn-Tucker (KKT) optimal condition, the optimal power allocation scheme is acquired for any size of the user pair [44], [47]. Fang *et al.* [26], Sun *et al.* [53], [54], and Fang *et al.* [55] study power allocation from the perspectives of energy efficiency (EE). Recently, [63] proposes an optimal power allocation scheme based on the game theory in UL PD-NOMA, where each user makes its own decision on its power level. Besides, [64] studies the power allocation with the mutual-coupled interference in heterogenous networks.

Meanwhile, considering the imperfect CSI at BS, paper [26] studies the optimal power allocation scheme and proposes the joint user scheduling and power allocation to maximize energy efficiency. Recently, the optimal power allocation for downlink PD-NOMA with both statistical and perfect CSI at the transmitter is studied, and an alternate optimization algorithm based on the KKT condition is proposed [56]. Zhu *et al.* [57] obtain the closed-form expression of optimal power allocation with the given user pairing over multiple channels. Moreover, the authors propose incorporating the user pairing algorithm in [55] with the optimal power allocation to jointly optimize the resource allocation of downlink NOMA. Furthermore, the research in [58] shows that the fundamental limitations of power allocation in PD-NOMA only depend on the minimum QoS and the total number of users that simultaneously served. Besides, in the mixed OMA and PD-NOMA system, the power allocation and user pairing are studied in [65].

2) RECEIVER DESIGN

It is fairness for NOMA with the SIC receiver to obviously improve the throughput of the cell-edge users [66] when reaching the equivalent total throughput in downlink. Similarly, in [28], the SIC receiver is considered as the baseline receiver, and the total throughput and the cell-edge user's throughput can be enhanced by 27% and 28% respectively in downlink. Higuchi [32] and Nonaka *et al.* [34] propose an intra-beam SIC for decoding the superposition codes of users in a random beamforming, which could be deployed in downlink MIMO-NOMA.

In [67], a SIC-free receiver design based on the joint-modulation transmission is presented for downlink NOMA. Compared with the symbol-level SIC receiver and code-level SIC receiver, the proposed receiver design can reduce almost a half computational complexity of both cell-edge users and cell-center users, and can get the same reliability as the code-level SIC receiver.

Furthermore, the SIC receiver and the joint decoding receiver are compared in [68] for uplink grant-free NOMA in machine-to-machine communications. According to the sporadic short packet transmissions of massive machines, it is necessary to consider the block fading multiple access channel and the frequency-selectivity. Thus, compared with SIC, joint decoding can achieve a higher throughput with high transmit power and good frequency-selectivity.

C. EVALUATIONS

1) ACHIEVABLE RATE

Achievable rate is a major indicator to evaluate the system-level performance of wireless systems. Saito *et al.* [51] evaluate the system-level performance of PD-NOMA by studying user rate in adaptive modulation and coding, hybrid automatic repeat request, and outer loop link adaptation wireless antenna interface configurations. Then it shows that the throughput gain of PD-NOMA is superior to OMA in these configurations. In addition, in the scenario where user rates are allocated opportunistically according to their channel conditions, the upper limit of the system throughput can be achieved by the opportunistic MA scheme [69]. Saito *et al.* [70] investigate the system-level performance of PD-NOMA in small cell deployments by studying the throughput performance gain. The simulation results show that the throughput gain of PD-NOMA obtained in the small cell is larger than that of OMA.

To verify the throughput gain, the average UE throughput and the cell-edge UE throughput of PD-NOMA are evaluated in [33] and [71]. It is pointed out in [33] that the gain of closed-loop MIMO is higher than that of open-loop MIMO in downlink. Besides, the sum rate performance of DL PD-NOMA is evaluated through the theoretical analysis and simulations in [72]. Recent research is paying more attention to user fairness limitations, which are often overlooked in the traditional PD-NOMA evaluations. For example, in [73], the optimal sum rate closed-loop expression of PD-NOMA with the consideration of user fairness is derived, and the sum rate of PD-NOMA and OMA from different channel conditions are evaluated.

2) BER/BLER

As PD-NOMA has been extensively studied, a number of evaluations on bit-error-rate (BER) have been carried out. In the case of two UEs, [33] and [71] verify that the validity of codeword-level SIC and the block-error-rate (BLER) performance of cell-center UE. The simulation results show that PD-NOMA with ideal SIC can achieve the same BLER performance as the one with codeword-level SIC. In addition, we also find out that the power of the cell-center user will affect the BLER performance. The simulation results show that the performance of the codeword-level SIC receiver is almost the same as that of the ideal SIC receiver. There is a clear gap between the symbol-level SIC receiver and the ideal SIC receiver, especially when the power allocation of the cell-edge user is high. In this case, the impact of error propagation cannot be ignored at the symbol-level SIC receiver. Furthermore, outage, instead of block error, reflects the failure delay-sensitive transmission of a user with given QoS. The outage probability in PD-NOMA, where a target data rate is assigned according to the respective QoS of users, is investigated in [69]. Moreover, the outage performance in a downlink NOMA is analyzed in [74], showing that a performance bottom line always exists under the network due to the limited feedback.

III. MC-NOMA

Different from SC-NOMA, MC-NOMA distinguishes users based on different codes and patterns, such as SCMA and PDMA. SCMA maps the coded bits of users directly into the multidimensional codewords in a sparse spread mode, and utilizes MPA at the receiver to achieve MUD. Meanwhile, PDMA adopts an unequal-diversity multi-user feature pattern matrix to realize non-orthogonal transmissions, and quasi-optimally distinguishes user signals by BP and BP-IDD at the receiver.

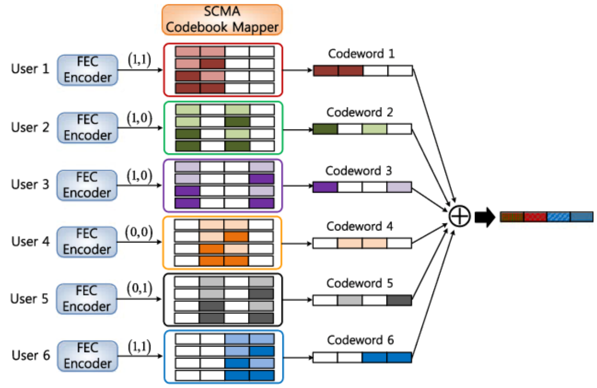

FIGURE 5. The encoding and multiplexing in SCMA (N=4, K=6) [103].

A. SCMA

SCMA adopts multi-dimensional modulation and sparse code spreading. Currently, SCMA could be deployed in both uplink and downlink to satisfy the massive connectivity requirements. In SCMA, each user signal can be mapped into two subcarriers to acquire the diversity and sparsity, which will increase reliability while decreasing receiver complexity.

1) BASIC PRINCIPLES

SCMA is an enhanced version of low density spreading code division multiple access (LDS-CDMA) proposed by Nikopour in [75], which has low-complexity at the receiver. In SCMA, the bit stream and propagation of quadrature amplitude modulation symbols are combined and mapped directly to the multi-dimensional codebooks, which have unique codewords for different users. As shown in Fig. 5, six users have different pre-defined codebooks. The codewords in one codebook for a particular user include two '0's in the specific position of subcarriers. In different codebooks, the positions of '0's are different to distinguish users. For each user, the data stream is mapped to the corresponding two subcarriers by a unique codeword. So that the data stream of six users can be transmitted on four subcarriers, following the superposition of corresponding codewords.

Different from LDS-CDMA, multidimensional constellations are designed to generate codebooks, resulting in a significant shaping gain. Here, the shaping gain refers to the increasing in average symbol energy when the shape of the constellation changes. Generally, when the shape of the constellation approaches the spherical surface, the shaping gain goes up. The maximum shaping gain achieved by optimizing a multidimensional constellation is 1.53 dB [1]. It is possible to obtain the shaping gain by optimizing the cascade method of the high dimensional modulation and generating the codebook based on the multidimensional constellation. Since the design of the multidimensional constellation is impossible to traverse, the SCMA codebook design is an ultra-complex problem. In addition, the optimal design criteria of multidimensional constellations are still hard to achieve. Currently, most research focuses on designing a suboptimal solution based on respective models.

The mathematical model of the SCMA system is similar to the one of the PDMA system. Thus, the detailed abstractions in DL and UL could refer to the ones in the Section III.B.1. Here, an example of the vital SCMA mapping matrix is given as follows

$$\mathbf{G}_{\mathrm{SCMA}} = (g_{n,k})_{N\times K} = \begin{bmatrix} 1 & 1 & 1 & 0 & 0 & 0 \\ 1 & 0 & 0 & 1 & 1 & 0 \\ 0 & 1 & 0 & 1 & 0 & 1 \\ 0 & 0 & 1 & 0 & 1 & 1 \end{bmatrix}, \tag{5}$$

where, the number of REs is denoted by N, the number of users is denoted by K; the RE allocation indicator $g_{n,k} = 1$ only if the signal of the k^{th} user is spread on the n^{th} RE; the vector of each column is unique and denotes the SCMA mapping pattern.

2) ENABLING SCHEMES

a: TRANSMITTER DESIGN

The transmitter design of SCMA focuses on the codebook design and resource allocation (including user paring), which might determine the reliability and decoding delay of the transmisson.

The codebook design, consisting of the design of the factor graph and the multidimensional constellation, is one of the most important components in SCMA. Since each user's codebook is rotated by a certain angle from the mother constellation, each user is pseudo-orthogonal. Thus, BS can distinguish users from different user subcarrier combinations. The system-level codebook design method is presented in [75] and [76]. With the multidimensional constellation and phase rotation, Yan *et al.* [77] propose a method to maximize the sum of distances between the dimensions of multiplexed codewords on different resources. In [78], A SCMA codebook is designed by optimizing the mapping matrix of the joint constellation. Zhou *et al.* [79] propose a codebook design method based on constellation rotation. Alam and Zhang [80] study the influence of energy diversity, system overload coefficient and codebook design parameters on SCMA performance. Then, the optimal design parameter set of mother constellation based on star quadrature amplitude modulation is proposed. Alam and Zhang [81] analyze the two key parameters of the minimum Euclidean distance and energy separation. Li *et al.* [82] summarize some criteria that can help to design the SCMA codebook by deriving the cutoff rate. Overall, it can be learned that various SCMA codebook design has been quite maturely studied to reach the target gain.

A linear sparse sequence is modelled to develop the pairing algorithm for MU-SCMA in [83], and MU-SCMA-related techniques are developed to pair users with shared time-frequency resources. The authors select paired users from the user pool, and design the corresponding selection criteria and optimization methods to transmit the superposed signal of the paired users. Zhai *et al.* [84] examine the tradeoff between data and power. An iterative algorithm based on univariate search under EE constraints is proposed to maximize the

TABLE 5. A Comparison of complexity reduction schemes at the receiver.

Reference	Type	Method	Performance
[88]	Iterative MPA	The special codebook structure and factor graph	Performance does not degrade with 300% load
[89]	Iterative MPA	Select t symbols in the m^{th} iteration which need not to be calculated in the rest iterations	Less than 0.3 dB loss in BLER performance
[90]	Weighted MPA	Introduce weight factors to replace MPA algorithm iterative process	Only a small BLER performance loss
[91]	Iterative MPA	Joint channel estimation, data decoding, and user detection	Reduce the decoding complexity substantially while negligible performance loss
[92]	Iterative MPA	Based on the list sphere decoding	Attain a near maximum likelihood (ML) performance with a substantially reduced decoding complexity
[93]	Hybrid BP and expectation propagation	Propose a convergence guaranteed receiver and two distributed cooperative detection schemes	Improve the BER performance by exploiting the diversity gain
[94]	Improved Partial Marginalization MPA	Reduce complexity based on partial marginalization MPA	Achieve the same performance with partial marginalization MPA
[95]	Discretized MPA	Discretize the probability density functions in the layer nodes	Achieve better performance than conventional MPA
[96]	Threshold MPA	The user in reliable set will no longer be updated	A small BLER performance loss with an appropriate threshold
[97]	Iterative EPA	Expectation propagation algorithm	Achieves similar BLER performance as the full MPA receiver
[98]	Iterative MPA	Gaussian approximation	Performance does not degrade much
[99]	MAX-Log MPA	Build a codebook by projecting the constellation to reduce dimension	Less than 0.5 dB BLER performance loss caused by the projection
[100]	Iterative MPA	Narrow the range of trusted constellation point	Maintain negligible BLER performance loss
[101]	Joint MP	Consider the channel gain and noise power to modify the joint MPA	Maintain negligible BLER performance loss
[102]	Joint sparse graph detection	Construct a joint sparse graph of MIMO and SCMA single graphs	Could achieve the optimal BLER performance as the ML detection
[104]	Modified sphere decoding detection	Applied the list modified sphere decoding to facilitate channel coding	Achieve the performance of the optimal ML detection with a lower average complexity compared with MPA

sum rate. The algorithm can achieve better rate-power tradeoff by adjusting the relevant parameters. Han *et al.* [85] make a related improvement based on the pre-existing resource allocation scheme of SCMA unlicensed uplink transmissions, and propose a resource allocation scheme based on the feedback for a continuous uplink transmission. Vameghestahbanati *et al.* [86] design and compare the multilevel polar coding and bit-interleaved polar coded modulation for UL SCMA to operate over fast and block fading channels. In [87], a resource allocation method for SCMA is proposed, and then an evaluation to compare the sum rate of SCMA and PD-NOMA is carrier out.

b: RECEIVER DESIGN

Due to the high complexity of MUD in traditional CDMA systems, the SCMA receiver needs to be designed to satisfy the massive connectivity. Thus, low density signature (LDS) and MPA are proposed to reduce the complexity of MUD.

However, the relatively high computational complexity of MPA is not sufficient to support the sparse structure of LDS. Consequently, it is necessary to look for a solution to reduce the complexity of MPA without significant degradation in BLER. In [88] and [89], the iterative multi-user receiver is proposed to take full advantage of the coding gain and the diversity gain, while the unique structure of SCMA codebook and the specific factor graph are used to reduce the decoding complexity. Wei *et al.* [90] propose a method to reduce the decoding complexity by introducing the weight factor instead of the MPA algorithm iterative process. This algorithm provides the original probability value associated with the distance between the received signal and the codeword, with low computational complexity. Further, Wei and Chen [91], [92] introduce the sphere decoding in the MPA detection to reduce the computational complexity of uplink grant-free SCMA. Besides, in [93], a graph-based low complexity MPA receiver is suggested for MIMO-SCMA system over frequency selective channels, which performances close to the MMSE-based receiver. In addition, in [94] and [95], the low complexity MPA detection algorithms are proposed for SCMA to reduce the computational complexity while keeping the BER at a sustainable level.

Yang *et al.* [96] propose a low-complexity MPA based on the threshold. All users are divided into reliable sets and uncertain sets, and it will be checked in the iterative process by a certain criterion. The decoded user will be placed in a reliable set, and the corresponding message will no longer be updated. A low complexity iterative receiver based on the expected propagation algorithm (EPA) is proposed in [97]. The complexity of the SCMA receiver is linear with the size of the codebook and the average degree of the factor nodes with the EPA. Tang *et al.* [98] propose an iterative receiver based on the Gaussian approximation and the Turbo structure.

Lu *et al.* [99] design a low complexity receiver based on the projection constellation with the reduced dimension. They project a 16-point constellation in different ways into two 9-point constellations, while distinguish each constellation point through the difference between the two 9-point constellations. In [100], a new MPA detector based on the ascending SCMA system is proposed. The MPA based on sphere decoding narrows the range of the trusted constellation point. Liu *et al.* [101] propose a blind detector that does not rely on the user sparseness of a priori information.

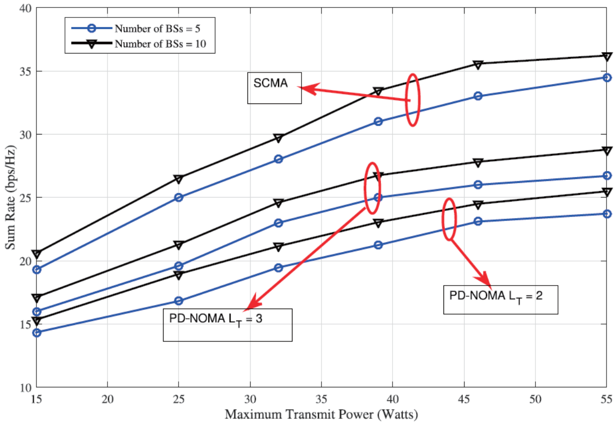

FIGURE 6. A sum rate comparison between SCMA and PD-NOMA [87].

Heo *et al.* [103] propose a new channel estimation scheme to solve the large amount of training overhead with the growth of the number of active users. The scheme reduces interference by the weighted regularization algorithm, and introduces the sparse pilot structure to realize the lower bound of mean square error. Moreover, in [104], a reduced-complexity optimal modified sphere decoding detection scheme is proposed to exploit the properties inherited from the structure of SCMA codebooks.

As can be seen from Table 5, current research in the SCMA receiver aims at maintaining the performance in various scenarios without increasing the complexity of the receiver. However, research on low-complexity receivers are worthy to be paid attention to, since they are more appropriate to be deployed in low-cost UEs.

3) EVALUATIONS

a: ACHIEVABLE RATE

Although SCMA has recently been extensively studied, the theoretical analysis of the achievable rate without error in downlink still lacks. Li *et al.* [82], under AWGN and Rayleigh fading, derive the cut-off frequency in downlink SCMA using the Hölder inequality and the classification of the pair of error events to achieve an accurate cut-off rate. Moreover, Huawei gave SCMA downlink level simulation results in 3GPP RAN1 #86 meeting [105]. SCMA can obtain a larger capacity domain than OFDMA, thereby improving system throughput in the single-user and multi-user situations. As shown in Fig. 6, SCMA can achieve a more than 20% gain in sum rate compared to PD-NOMA.

b: BER/BLER

In SLS, the estimation on BLER is complicated when adding a variety of technologies, including the variable modulation coding scheme [106]. Bao *et al.* [107] evaluate the error performance of multidimensional constellations in multiple access and broadcast channels. In the AWGN channel, the analysis boundary of the combined ML receiver is consistent with the simulation boundary in the high SNR region. The BER gap between the MPA receiver and the ML receiver is close to 0.4 dB at 14 dB SNR. The performance of the MPA receiver is asymptotically improved and is close to the performance of the ML receiver at the high SNR region. Furthermore, in [108], a tight upper bound on the probability of symbol detection error is derived with receiving diversity and randomly distributed users.

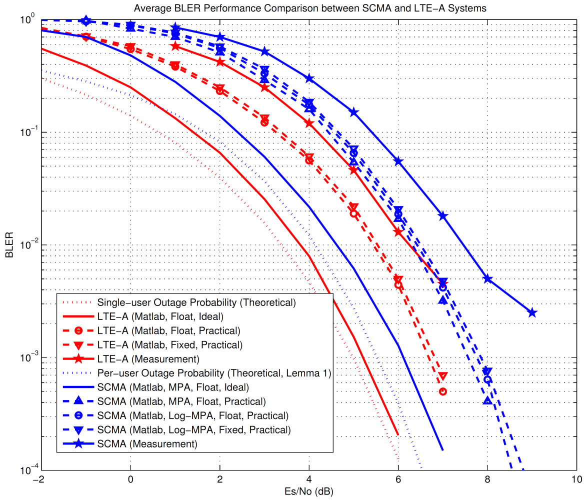

FIGURE 7. A BLER comparison of SCMA and OMA in LTE-A [110].

Yu *et al.* [109] evaluate BER on the star constellation in the AWGN channel. The expression of BER are deduced from statistics of the phase angles in SCMA constellation. The simulation result is slightly deviate from the theoretical analysis results in the low SNR region, while matches well in the high SNR region.

In Fig. 7, we can see the negligible performance loss caused by 16-bit fixed-point quantization and by replacing MPA with low complexity Log-MPA algorithm. The BLER measurement results from the prototype system show less than 1 dB performance gap if compared with the fixed-point simulation results [110]. Seen from the existing evaluations, the advanced MPA receiver has better BER performance than the SIC-MPA receiver in SCMA, while SCMA with SIC-MPA receiver has better BER performance than OFDMA.

B. PDMA

PDMA, which can simultaneously utilize resources in the time/frequency/space domain, is proposed in [111]–[113] and further investigated to increase the number of accessed UEs. PDMA is a typical MC-NOMA technology, in which the user signals can be multiplexed into different numbers of subcarriers. In addition, the same coded bits from one UE are mapped onto different subcarries with power scaling or phase rotation (a variance of repetition), which could increase reliability by utilizing the advanced receiver with maximum-ratio combining and BP. Moreover, we can reveal that SCMA is a special specie of PDMA. When the number of subcarriers

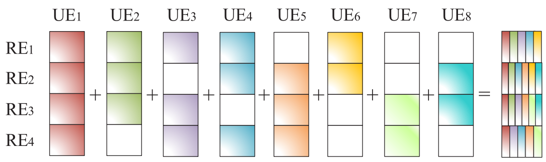

FIGURE 8. The case of 8 users mapping on 4 REs.

occupied by each user is less than three, PDMA will degenerate into SCMA. For reducing system complexity, the data of users should be sparsely mapped onto different subcarriers.

1) BASIC PRINCIPLES

Assuming K users are superposed on N available REs in PDMA with a special pattern. The design of PDMA can be represented by a $N \times K$ characteristic pattern matrix. For simplification, in [111] and [112], the indicative function of elements in the characteristic pattern matrix $\mathbf{G}_{\text{PDMA}} \in \mathbb{N}^{N\times K}$ is denoted as

$$\mathbf{G}_{\text{PDMA}} = \begin{bmatrix} 1 & 1 & 1 & 1 & 0 & 1 & 0 & 0 \\ 1 & 1 & 0 & 1 & 1 & 1 & 0 & 1 \\ 1 & 1 & 1 & 0 & 1 & 0 & 1 & 1 \\ 1 & 0 & 1 & 1 & 1 & 0 & 1 & 0 \end{bmatrix}. \tag{6}$$

The multi-user signals are superposed according to the PDMA characteristic pattern matrix at the transmitter, which can also be referred as the PDMA mapping, as shown in Fig. 8.

We can see that data of the 1st user are mapped to all four REs. The data of the 2nd user are mapped to the 1st RE, the 2nd RE, and the 3rd RE, and so on. The order of transmission diversity (the number of '1's in the corresponding column of indicative pattern matrix $\mathbf{G}_{\text{PDMA}}$) of the eight users is 4, 3, 3, 3, 3, 2, 2, and 2, respectively.

We can also find out that, the more degrees of diversity one user has, the more reliable data transmission can be expected, and the signal of this user should be decoded in prior. Therefore, to design the optimal PDMA pattern matrix, the overloading factor, diversity and the complexity of detection should be taken into consideration jointly.

a: DOWNLINK PDMA

The downlink PDMA system is shown in Fig. 9. Here, we assume that one single antenna is equipped at the receiver and one antenna is chosen at the transmitter to send the superposed signals.

At the transmitter, the signals of different users are mapped to allocated REs according to the PDMA characteristic pattern matrix.

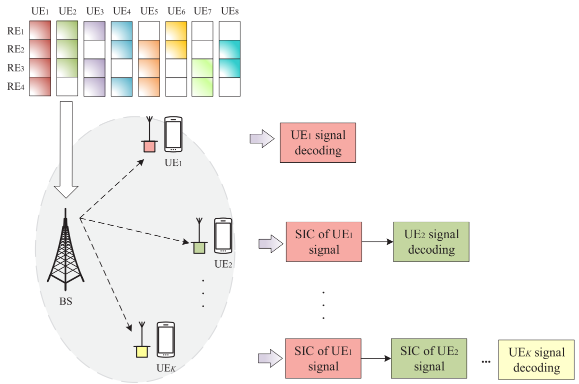

FIGURE 9. The system model of downlink PDMA.

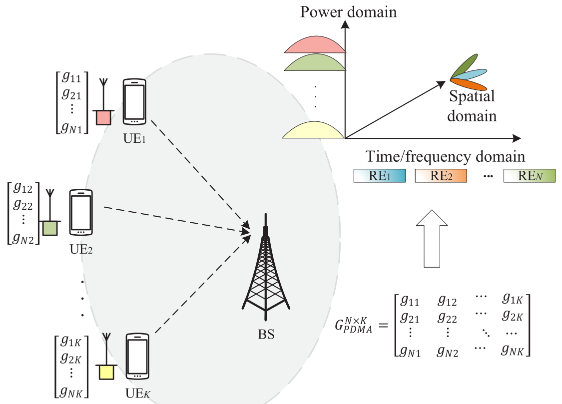

FIGURE 10. The system model of uplink PDMA.

At the receiver, MUD scheme based on SIC is used to separate multi-user signals. Without loss of generality, we assume that the users are decoded in an increasing order of their indexes, that is, the 1st user decodes its own signal, regarding the other users' signals as noise. And, the 2nd user first decodes the 1st user's signal, then decodes its own signal by subtracting the reconstructed signal of the 1st user from the received signal.

Then, the received signal on all REs at the k^{th} user can be denoted as

$$\mathbf{y}_k^{\text{DL}} = diag(\mathbf{h}_k^{\text{DL}})\mathbf{G}_{\text{PDMA}}\mathbf{x}^{\text{DL}} + \mathbf{n}_k^{\text{DL}}, \tag{7}$$

where $\mathbf{x}^{\text{DL}} = [x_1, x_2, \ldots, x_K]^T$ is the transmit data for all the users, and $\mathbf{n}_k^{\text{DL}} = [n_{1,k}, n_{2,k}, \ldots, n_{N,k}]^T$ is noise at all REs of the k^{th} user; $\mathbf{h}_k^{\text{DL}} = [h_{1,k}, h_{2,k}, \ldots, h_{N,k}]^T$ represents the channel coefficients vector from the base station to the k^{th} user on all N REs, and $diag(\mathbf{h}_k^{\text{DL}})$ represents the diagonal matrix with diagonal elements from $\mathbf{h}_k^{\text{DL}}$.

b: UPLINK PDMA

As shown in Fig. 10, we consider the PDMA uplink system with K users transmitting to a BS over N REs. We assume that, each user is equipped with a single antenna and BS is equipped with M antennas to achieve diversity receiving. At the k^{th} user, coded symbol x_k is mapped to corresponding REs according to PDMA characteristic pattern matrix $\mathbf{G}_{\text{PDMA}}$.

Therefore, we can get the received signal in the m^{th} BS antenna as follows

$$\mathbf{y}_m^{\text{UL}} = (\mathbf{H}_m^{\text{UL}} \odot \mathbf{G}_{\text{PDMA}})\mathbf{x}^{\text{UL}} + \mathbf{n}_m^{\text{UL}}, \tag{8}$$

where $\mathbf{x}^{\mathrm{UL}} = [x_1, x_2, \cdots, x_K]^T$ is a vector representing coded symbols of all K users, and $\mathbf{n}_m^{\mathrm{UL}} = [n_{1,m}, n_{2,m}, \cdots, n_{N,m}]^T$ represents the noise in the m^{th} BS antenna; $\mathbf{H}_m^{\mathrm{UL}}$ represents the uplink channel coefficients matrix between all users and the m^{th} BS antenna. Meanwhile, $\odot$ indicates the element-wise product of two matrices.

In most cases, no CSI is obtained at UEs. Then, transmit power is always equally allocated between different available REs. On the other hand, with ideal channel state information at the user side, we can design the optimal uplink characteristic pattern matrix to fully utilize the multi-user diversity in the frequency-selective channel.

2) ENABLING SCHEMES

a: TRANSMITTER DESIGN

The design of the PDMA pattern matrix, which is important, reflects the mapping method, transmission diversity order and overload factor. Chen *et al.* [111] firstly provide some criteria to design the PDMA pattern matrix. Following the criterion of maximum constellation-constrained capacity, they design the optimal PDMA pattern matrix in uplink. In addition, to reduce the ambiguity caused by the combined constellation, the authors apply the power scaling and phase shifting techniques to extend the PDMA pattern matrix. Subsequently, Ren *et al.* [114] propose the design criteria of the optimal PDMA pattern matrix in uplink mMTC and eMBB. According to the diversity requirement of mMTC and eMBB, the authors adopt the sum squared correlation and the constellation-constrained capacity as the metrics.

In downlink PDMA, Mao *et al.* [115] utilize quasi-orthogonal space-time block code with different diversity orders to alleviate the error propagation in the SIC detector for each user, and then use power allocation for multiple users with diverse channel gains to increase the spectrum efficiency. Besides, in order to improve the sum throughput of the downlink PDMA, Zeng *et al.* [116] solve the optimization problem of jointing pattern assignment and power allocation design through the iterative water-filling algorithm. So far, the computational complexity is extraordinary high to search the optimal pattern matrix. A low complexity method for a sub-optimal PDMA pattern matrix is necessary to be developed.

The random interleaver enhanced PDMA (RIePDMA) scheme is proposed in [117] to support massive connectivity. The RIePDMA system is formed by adding interleavers between the channel encoder and the PDMA encoder to bring in the advantages of the random interleave (RI). Since RI not only confronts fight the channel fading, but also avoids consecutive errors caused by insignificant interference while disturbing the order of encoder bits. Therefore, RIePDMA can obtain better performance than PDMA when the overload factor is higher, which means RIePDMA is sufficient to support massive connectivity.

Additionally, the PDMA improved with the large-scale antenna array scheme is proposed in [118], in which the authors use power allocation in pattern mapping to increase the system throughput and utilize the beam allocation to improve the connectivity. Furthermore, Tang *et al.* [119] study the resource allocation and transmission mechanism of the uplink grant-free PDMA, and demonstrate that the grant-free PDMA scheme can efficiently support massive connections in mMTC.

TABLE 6. **A Comparison of the receiver algorithms in PDMA.**

Detector algorithm	Interference cancellation	Iterator	Computational complexity
BP (MPA)	No	Inner	Low
BP-IDD	No	Inner and outer	Normal
BP-IDD-IC	Yes	Inner and outer	Low (high SNR region)
SIC	Yes	No	Lowest
MMSE-IC	Yes	No	Low
ML-IC	Yes	No	Highest

b: RECEIVER DESIGN

To mitigate the inter-user interference caused by the superposition of signals exists in PDMA, advanced receivers are designed. Thus, the BP algorithm emerges and quickly grows up. On the one hand, the sparsity in the PDMA pattern can cut down the complexity of the receiver with BP. On the other hand, the different transmission diversity orders of PDMA can expedite the convergence of BP [111]. Furthermore, the BP-based detector algorithms, such as BP-IDD [120] and BP-IDD-IC [117], are proposed to reduce BLER by adding outer iterators and/or the IC module. In addition, the receiver is also enhanced by SIC like IC schemes to get better performance, such as ML-IC, MMSE-IC [121], and BP-IDD-IC. Besides, PDMA with the parallel interference cancellation receiver scheme is proposed in [122], which can achieve 17.64% SNR gain over the PDMA with SIC at the cost of two or three iterations. Furthermore, Jiang *et al.* [123] propose the PDMA joint transmitter and receiver design based on the power domain and beam domain.

As shown in Table 6, the individual characteristics and the complexity of the receiver algorithms are compared. Considering the computational complexity and the performance of the detector algorithms, the BP and SIC algorithms are suitable for PDMA with the sparse PDMA pattern and the low overload factor. BP-IDD and MMSE-IC have good performance with adequate complexity at the receiver. The BP-IDD-IC has a great advantage in the high SNR region. Besides, the ML-IC algorithm can get the optimal detection at the cost of high computational complexity at the receiver. Therefore, the ML-IC algorithm is appropriate for high-reliable communications. In general, we can choose different suitable receiver algorithms to fulfill the various constraints of different communication scenarios.

3) EVALUATIONS

a: ACHIEVABLE RATE

Chen *et al.* [111] accomplish LLS and SLS to compare the SE of PDMA and conventional OMA scheme and find

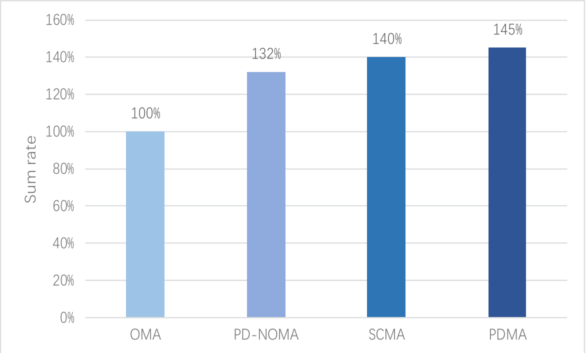

FIGURE 11. yA sum rate comparison of OMA, PD-NOMA, SCMA, and PDMA (TDL-C 300ns channel model, ideal channel estimation, UL, 1Tx2Rx,4 PRB) [126]–[129].

out that PDMA gains more than 20% in sum rate in both uplink and downlink. The existing numerical results show that uplink PDMA, in burst short packet traffic, can support almost five times more connections than OFDMA, under a given BLER at 1%. PDMA achieves a more than 30% gain over OFDMA in sum rate in downlink. Besides, in [113], when the constellation-constrained sum rate is analyzed and evaluated, the authors reveal that, there exists a 50 percent sum rate increment in the PDMA scheme with a simple 2×3 PDMA matrix. Then, a sharp decrease in the complexity of the receiver could be obtained at the same time. Moreover, theoretical analysis results of the achievable rate in uplink PDMA with 3 users mapping on 2 REs are shown in [124] and [125], and the PDMA can acquire a 150% gain over OMA when setting all the user with the same target data rate.

Fig. 11 shows the sum rate performance comparison between OMA, PD-NOMA, SCMA, and PDMA. As shown in Fig. 11, MC-NOMA can achieve a higher sum rate than OMA and PD-NOMA, where the gains of SCMA and PDMA to OMA are 40% and 45%, respectively.

b: BER/BLER

The evaluations on BLER in the existing PDMA schemes are intensively underway. In [114], the LLS results show that the PDMA pattern matrix designed for mMTC with a smaller value of the sum squared correlation achieves lower BLER. Besides, the PDMA pattern matrix designed for eMBB with a bigger maximum row weight and a higher dimension, which increases detection complexity, can acquire better BLER performance because of the higher frequency diversity. Due to the increasing detection complexity for lower BLER, a trade-off should be taken into account in the PDMA pattern matrix design in practical eMBB scenarios.

Furthermore, the LLS in [117], [130], and [131] verify that PDMA outperforms conventional OMA in BLER. Fig. 12 shows the BLER performance comparison between OMA, PD-NOMA, SCMA, and PDMA. As shown in Fig. 12, MC-NOMA can get better performance than OMA and PD-NOMA, and the BLER of PD-NOMA is more than 25% higher than SCMA and PDMA when the received SNR is 4 dB.

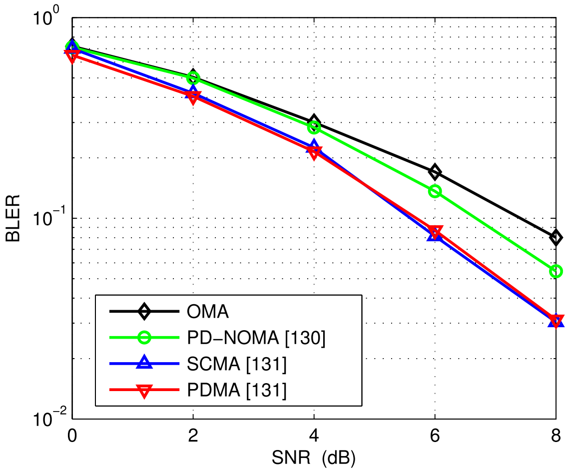

FIGURE 12. A BLER comparison of OMA, PD-NOMA, SCMA, and PDMA (TDL-C 300ns channel model, ideal channel estimation, UL, 1Tx2Rx,4 PRB) [130], [131].

The evaluations work of BLER performance in the uplink PDMA system is gradually improving. Dai *et al.* [113] evaluate the average BLER performance of all users in PDMA with different overload factors through LLS. The BLER performance of PDMA outperforms that of OMA with different overload factors when received SNR is larger than 3 dB. Besides, Zeng *et al.* [124] and Tang *et al.* [125] theoretically analyze the outage performance of uplink PDMA with 3 users mapping on 2 REs. Moreover, the BLER performance of the uplink grant-free PDMA scheme with several different collisions is compared with the grant-free OMA scheme through LLS in [119]. When encountering less than three-times collisions, the loss in the BLER performance of grant-free PDMA is insignificant, and the BLER performance of grant-free PDMA always outperforms that of grant-free OMA.

IV. APPLICATIONS

In this part, we investigate the most promising applications of NOMA in the 5G era. It should be pointed out that, the applications of SC-NOMA are studied comprehensively, but the research on the applications of MC-NOMA is still in progress. Nevertheless, the current research topics of SC-NOMA can guide the road to the future of MC-NOMA.

A. SC-NOMA

In this part, we show the ability of SC-NOMA in cooperating well with other 5G key technologies, such as MIMO, cooperative communications, mmWave, and UDN.

1) MIMO-NOMA

PD-NOMA combined with MIMO provides an efficient approach, MIMO-NOMA, to meet the explosive growth in traffic volume. Benjebbour *et al.* [71] first investigate the application and interface design of PD-NOMA in the downlink of single-user MIMO. Ali *et al.* [37], and Liu and Wang [49] further study the application of NOMA in multi-user MIMO. Al-Abbasi *et al.* [132] investigate the resource allocation in multi-user MIMO-NOMA with interference alignment. Li *et al.* [133] study the MIMO-NOMA system in the Nakagami-m fading channel and propose a joint antenna selection scheme to minimize the outage probability. Besides, multi-cell MIMO-NOMA can further improve SE. Therefore, Shin *et al.* [134] propose an interference channel alignment based NOMA, which can support any number of cells and minimize inter-cell interference. Subsequently, Shin *et al.* [135] propose cooperative beamforming based on interference alignment and cooperative beamforming based on interference channel alignment in multi-cell MIMO-NOMA.

In [136], the rate region and resource allocation of MIMO-NOMA in two typical network structures are studied. In [137], the sum channel capacity of the MIMO-NOMA is theoretically verified higher than that of the MIMO-OMA, and the same conclusion can be obtained in the ergodic sum capacity. In addition, Zeng *et al.* [138] study the energy-efficient PA in MIMO-NOMA with a minimum user rate constraint, and give the closed-form expression of PA to maximize the sum rate. Meanwhile, in [137] and [138], the low-complexity user admission schemes are studied to optimize the number of admitted users and the sum rate under a given SINR threshold or a minimum user rate constraint.

Recently, Huang *et al.* [139] give a review on the current MIMO-NOMA research. When focusing on the key principles of beamforming, user pairing, and power allocation. Furthermore, the authors discover the limitations of MIMO-NOMA in existing work, such as SIC-stability.

2) COOPERATIVE PD-NOMA

Cooperative PD-NOMA (C-NOMA) with a dedicated relay can overcome the large path loss and deep fading, thereby reducing the outage probability. For example, the asymptotic outage probability of C-NOMA is studied in [140] with a dedicated amplify-and-forward relay. The results verify that C-NOMA achieves the same diversity order and superior coding gain compared to cooperative OMA. Furthermore, to ensure that multi-user could be served simultaneously, a collaborative PD-NOMA assisted relaying system, which contains source-relay and relay-destination NOMA links, is proposed in [141]. Ding *et al.* [142] propose a C-NOMA transmission scheme, in which the user with better channel conditions has previous information about other users' messages. Zhang *et al.* [143] study the optimization of downlink PD-NOMA with cooperative full-duplex relays, in which near-users act as full-duplex relays to cell-edge users. Besides, Ali *et al.* [144] study the distributed power allocation of the coordinated multipoint transmission technology in downlink multi-cell NOMA and verify the applicability and requirements of the application. Recently, Nguyen *et al.* [145] analyze the joint design of collaborative transmitting and decoding of NOMA in the wireless backhaul two-tier HetNet, considering transmit beamforming at macro BS and the power allocation at small cells. Jha and Kumar [146] and Wang *et al.* [147] study the performance of C-NOMA scheme from the perspectives of different fading channels.

3) MMWAVE-NOMA

High-directionality and massive connectivity in the mmWave transmission call for the combination of mmWave and PD-NOMA. In [148], the mmWave-NOMA scheme is proposed to reduce the system overhead by two random beamforming approaches. The sum rate and outage probability of the proposed scheme outperform these of conventional mmWave-OMA schemes. In addition, finite resolution analog beamforming can reduce hardware costs in mmWave network. Therefore, the beamformers are not completely aligned with the channels of users, and multiple users may be assigned similar or even identical beamformers. Marcano and Christiansen [149] further study the capacity gain of mmWave-NOMA. Compared to conventional OMA, PD-NOMA can achieve a nearly 70% gain in capacity. Recently, Yi *et al.* [150] propose the novel analytical expressions for the coverage and system throughput in mmWave-NOMA, especially in plentiful noise-limited scenarios.

4) PD-NOMA WITH SWIPT

Many researchers try to combine the simultaneous wireless information and power transfer (SWIPT) technology with PD-NOMA to save the energy of the communication devices [151]–[153]. Xu *et al.* [151] investigate the application of SWIPT in PD-NOMA, and propose a new cooperative protocol to maximize the data rate of the cell-center user while meeting the QoS requirements of the cell-edge user. Besides, Ye *et al.* [152] propose a new power allocation protocol for energy harvesting relays.

5) PD-NOMA IN UDN

UDN is one of the technologies that are hopeful to address high-throughput and large connection numbers scenarios. In addition, multiple access points (APs) in PD-NOMA can be multiplexed on the same power domain to provide high data rate services to multiple users. Liu *et al.* [154] apply PD-NOMA in UDN to optimize multi-user access. In that paper, the authors give correlation APs and REs to multiple users based on a matching algorithm to maximize system throughput. Next, power allocation is performed by using difference of convex programming. Recently, Liu *et al.* [155] propose a user-centric PD-NOMA framework to provide the high area throughput density and flexible access in UDN. Then, a low complexity sub-optimal algorithm based on matching is proposed by transforming the mixed integer nonlinear programming problem to an access points grouping problem. Besides, the user pairing and resource allocation of PD-NOMA are studied to enable the flexible configuration in heterogeneous UDN in [156].

6) OTHERS

Currently, there are many other emerging PD-NOMA applications. PD-NOMA are applied to obtain the massive connectivity under the internet-of-things scenarios, such as machine-to-machine [68], vehicle-to-vehicle [157] or vehicle-to-everything [158] scenarios. In addition, applying PD-NOMA to visible light communication [159], [160] and satellite communication [161], [162] is under way.

B. MC-NOMA

Here, we will describe potential scenarios in which MC-NOMA will be applied, such as device-to-device (D2D), MIMO, SWIPT, and cooperative communications. Currently, there is no mature theoretical basis in these application scenarios. Nevertheless, we believe the current well-researched applications of SC-NOMA can inspire and motivate the combinations of MC-NOMA with other 5G techniques in different deployments.

1) MIMO-SCMA

It can be expected that the combination of SCMA and MIMO will greatly improve SE of mobile systems. Du *et al.* [102] point out that MIMO is one of the key enabling technologies in SCMA. In downlink MIMO-SCMA, the near-optimal detector is made up of a combined sparse graph of the combined MIMO, SCMA single graphs, corresponding virtual codebook, and MPA based joint processing.

At present, the rapid change of channel parameters makes it difficult to estimate the channel, which seriously influences BLER in MIMO-SCMA. Therefore, in practical applications, there is still much room for the research of MIMO-SCMA to overcome the channel fading. When deploying the MIMO-SCMA in multiple cells, it may be difficult to alleviate the inter-cell interference. By referring to the technologies in MIMO-NOMA, the interference alignment technology may be utilized in MIMO-SCMA to eliminate the inter-cell interference.

2) COOPERATIVE MC-NOMA

It is efficient to combine the cooperative communication technique with SCMA. In [163], a novel distributed cooperation method based on the dual-tier communication is studied in the SCMA system. Luo *et al.* [164] research the optimization of resource allocation in the dual-hop relay assisted multiuser SCMA uplink network, and an alternative algorithm is proposed to maximize the weighted sum-rate considering combined power allocation, codebook assignment and subcarrier pairing. Han *et al.* [165] inventively combine SCMA with full-duplex MIMO relay, and ease the self-interference by time-domain cancellation and space-domain suppression.

The cooperative communication technique could also be combined with PDMA. Tang *et al.* [166] propose a cooperative PDMA (C-PDMA) uplink model with the half-duplex decoding and the forward relay. Additionally, they derive the corresponding closed-form expression of outage probability. Then, the authors prove that C-PDMA can achieve an obvious gain in the matter of outage probability compared to non-cooperative PDMA and cooperative OMA. In addition, the C-PDMA with DF relaying in DL is proposed in [167], where the authors derive the closed-form expression of outage probability and analyze the performance of downlink C-PDMA.

So far, the resource allocation in downlink cooperative MC-NOMA remains an unsettled problem, since the inter-user interference fluctuates while the SIC is inefficient. Researchers might refer to the algorithms in cooperative SC-NOMA to enhance the resource allocation of cooperative MC-NOMA.

3) MMWAVE-SCMA

Since new spectrum bands are vital to satisfy exploding traffic demands in SCMA, the mmWave-SCMA is studied in [168], and then a joint spectrum sensing and subcarrier adaptation scheme is applied in the mmWave-SCMA system to avoid mutual interference between 5G and other existing networks.

4) SCMA WITH SWIPT

The emerging of SWIPT has inspired researchers to explore the interest of energy-saving networks. With SWIPT, the cost of wires and cables can be reduced, and the charging issue could be eased. For medical applications based on implantable diagnostic sensors, wireless energy delivery makes the patient more convenient. Zhai *et al.* [84] propose a resource allocation scheme that combines SCMA and SWIPT to balance between data rate and energy. In the paper, energy harvesting is used to optimize the energy efficiency. In addition, the authors propose an iterative algorithm based on optimized power allocation and pattern matrix to reduce computational complexity.

Considering the SWIPT technique applied in SC-NOMA, dynamic energy-harvesting algorithms have the ability to guarantee the target data rates of users as well as improve the energy efficiency, which may be useful for the combination of SCMA and SWIPT.

5) SCMA IN D2D

D2D and cellular hybrid networks are promising candidate technologies for achieving massive connectivity. Liu *et al.* [169] apply SCMA to a D2D communication and cellular hybrid network. The random geometry model is applied to represent the location of BS and UEs in a hybrid network. The authors propose an analysis framework to calculate the influence of key parameters on hybrid networks. Besides, in the underlying model, the authors study the resource allocation and the optimal activation probability, and summarize the optimal codebook allocation criterion. In addition, Dai *et al.* [170] use hypergraph to describe the interference among cellular uplinks and D2D links when SCMA is applied, and then they propose a hypergraph based resource allocation algorithm. Zhao *et al.* [171] consider a cooperative mode selection and resource allocation problem in the scenario where multiple D2D users are allowed to share SCMA codebooks.

When applying SCMA to D2D communications, the requirements of low latency and high reliability would become a bottleneck. Inspired by the application of PD-NOMA in the vehicle-to-vehicle communication, the semi-persistent scheduling technique and distributed power control technique, which has iterative signaling control, may become the potential solution of this bottleneck.

V. CONCLUSION

In this paper, we have presented the research progress of NOMA from the perspectives of single-carrier and multi-carrier, with a comprehensive overview of the MC-NOMA development and application. Compared with the performance of traditional OMA techniques, SC-NOMA and MC-NOMA can provide higher SE and achievable rate. So far, SC-NOMA has been studied maturely, but there is still a long way to go in the research of MC-NOMA.

Although we have listed some existing simulation results of MC-NOMA schemes, current evaluations mainly focus on LLS. Thus, there is still much work to be carried out in SLS of MC-NOMA. In addition, the evaluations of other aspects, such as the outage probability and EE of MC-NOMA should be reserved as future research topics. Furthermore, we have investigated the potential applications of the MC-NOMA, and discovered that the implementations of MC-NOMA could be inspired and accelerated by the well-researched SC-NOMA applications combined with various techniques in different scenarios.

Meanwhile, as mentioned in Section IV, we can find out that the integration of MC-NOMA with other 5G technologies has shown advantages, while some bottlenecks exist. Considering the technical maturity level, OFDMA will be very likely to be deployed in 5G wireless systems. Therefore, the MC-NOMA technology, which combines the features of NOMA and OFDMA, has been frequently mentioned as a competitive candidate.

Moreover, the research on applying MC-NOMA with other communication technologies, especially other 5G key technologies, is still in its infancy. In our own opinion, downlink cooperative MC-NOMA, MIMO enhanced MC-NOMA, mmWave based MC-NOMA, and the deployment of MC-NOMA in UDN could be explored further and have great applying prospects in the 5G era.

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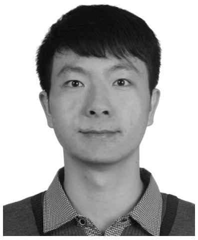

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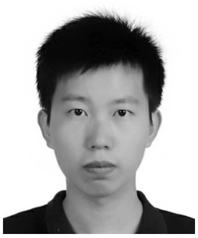

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