A Survey of Rate-optimal Power Domain NOMA Schemes for Enabling Technologies of Future Wireless Networks

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Abstract—Non-orthogonal multiple access (NOMA) schemes serve more than one user in the same resource block by multiplexing users in other domains than frequency and time. In this way, NOMA schemes offer several advantages over orthogonal multiple access (OMA) schemes such as improved user fairness and spectral efficiency, higher cell-edge throughput, massive connectivity support, and low transmission latency. With these merits, NOMA transmission schemes are being increasingly looked at as a promising multiple access scheme for future wireless networks. When the power domain is used to multiplex users, it is referred to as the power domain NOMA (PD-NOMA) scheme. In this paper, we survey the integration of the PD-NOMA scheme with other upcoming communication schemes and technologies that satisfy the requirements of 5G and beyond 5G (B5G) networks. In particular, this paper surveys the rate optimization schemes studied in the literature when the PD-NOMA scheme is combined with MIMO and massive MIMO (mMIMO), millimeter wave (mmWave) communications, coordinated multi-point (CoMP) transmission and reception, cooperative communications, cognitive radio (CR), visible light communications (VLC), and unmanned aerial vehicle (UAV) assisted communications. The considered system models, the optimization methods used to maximize the achievable rates, and the main outcomes on the performance of these NOMA-enabled schemes are discussed along with future research directions for these combined schemes.

Index Terms—Non-orthogonal multiple access (NOMA), 5G and beyond 5G networks, achievable rates, optimization, power allocation, user selection, beamforming, MIMO, massive-MIMO (mMIMO), millimeter-wave (mmWave), coordinated multi-point (CoMP), cooperative communications, cognitive radio (CR), visible light communications (VLC), unmanned aerial vehicle (UAV).

I. INTRODUCTION

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Future wireless networks such as the fifth-generation (5G) and beyond 5G (B5G) cellular networks are expected to support extremely high data rates and a very large number of users. However, the multiple access technologies of the past generations of cellular networks will not scale to meet this unprecedented demand for network traffic. The multiple access schemes used to date in cellular networks include frequency division multiple access (FDMA) in 1G systems, time division multiple access (TDMA) in 2G, code division multiple access (CDMA) in 3G and recently orthogonal frequency division multiple access (OFDMA) in 4G. The common theme in all these multiple access schemes is “orthogonality” where, theoretically, the different users do not interfere with one another when they access the network resources. However, this insistence on orthogonality poses a limit on the number of users that can access the network resources and thereby reduces the overall spectral efficiency. Non-orthogonal multiple access (NOMA) schemes, on the other hand, allow multiple users to share the same resource (e.g., a time/frequency resource block) and separate the users in other domains with some additional receiver complexity. When the power domain is used to separate the users, it is referred to as the power-domain NOMA (PD-NOMA) [1] scheme and is the focus of this paper. Alternatively, if the users are separated through non-orthogonal codes, it is referred to as code-domain NOMA (CD-NOMA) [2], [3]. PD-NOMA has also been studied in conjunction with CD-NOMA recently [4], [5], where such combination is beyond the scope of this survey paper.

To support the large explosion of connected users forecast in the massive machine type communication (mMTC) paradigm of 5G and beyond networks, interest has been growing in academia, industry and even standardization bodies like 3GPP to adopt NOMA schemes [6]. Compared to orthogonal multiple access (OMA) schemes, NOMA and hybrid NOMA-OMA schemes have the following attractive merits for 5G [3], [7] and B5G networks:

• Improved spectral efficiency; as multiple users of the networks that adopt NOMA schemes can occupy the entire bandwidth which is not applicable in multi-user networks that utilize OMA schemes. Moreover, in OMA schemes, the resource block might be allocated to a user with a poor received signal strength leading to reduced spectral efficiency.

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• Improved user fairness; as NOMA schemes can accommodate multiple users in the same resource block with guaranteed minimum rate requirements. On the contrary, OMA users with poor channel conditions might not be served for a long time by a scheduler trying to optimize the overall spectral efficiency.

• Low transmission latency; as the users in the networks that adopt OMA schemes need to wait for an available orthogonal resource block to grant access for transmission. In contrast, NOMA schemes offer more flexible user scheduling opportunities as well as grant-free transmission.

• Higher cell-edge throughput; as NOMA schemes allow a base station (BS) to flexibly change the fraction of power allocated to a cell-edge user to support a certain quality of service (QoS), which accordingly enhances its transmission rate.

With its promising performance, NOMA is considered as a candidate multiple access scheme in various standardization activities. For long term evolution advanced (LTE-A) systems (3rd Generation Partnership Project (3GPP) release 13), NOMA was considered under the name of multi-user superposition transmission (MUST) [8]. Furthermore, in LTE-A Pro (3GPP release 14), the standardization body recognized that at least uplink NOMA schemes should be considered especially for mMTC [9]. In 5G new radio (NR) phases (1 & 2) (3GPP release 15 and release 16) [10], [11], multiple studies on the advancements needed in the transmitter and receiver sides for adopting NOMA schemes have been proposed. In addition, some link-level and system-level performance evaluations that show the potential of adopting NOMA schemes have been conducted there.

Further, apart from NOMA schemes, several other PHY technologies and network architecture paradigms are brewing in the literature to meet the high data rate demands of future wireless networks. These include massive multiple-input multiple-output (mMIMO), millimeter wave (mmWave) communications, coordinated multi-point (CoMP) schemes, cooperative communication, cognitive radio communication systems, visible light communication (VLC) systems and unmanned aerial vehicle (UAV) assisted communication systems. All these technologies can be integrated with PD-NOMA schemes in one form or the other and is not simply the addition of two existing technologies as discussed in detail in [12]. In this paper, we take this discussion of PD-NOMA-based schemes for emerging 5G technologies and examine how it leads to different rate optimization problems than what exist in the literature of conventional NOMA schemes or of OMA-based schemes. In other words, we survey the vast body of recent literature on rate optimization in such a combined setting of PD-NOMA schemes with these emerging technologies. It is worth mentioning that while some of these technologies like MIMO and mmWave have already made it to the existing 5G standard [6], their integration with NOMA is very much a future 5G network concept. Other technologies on the other hand like VLC and UAV are quite future-looking technologies on their own, and arguably, their integration with NOMA is even more futuristic.

In this paper, our contribution is to present a comprehensive up-to-date review on the integration of PD-NOMA schemes with MIMO/mMIMO, mmWave, CoMP, cooperative communication, cognitive radio, VLC, and UAV communication schemes to maximize the achievable rates and hence the spectral efficiency in current and future wireless networks. The rate optimization problems in such NOMA-enabled schemes are typically non-convex and their level of complexity increases as the number of system parameters get large. Hence, in this survey, we present the adopted system model and specify optimization techniques utilized for each category in the above list of NOMA integrated technologies. In each category, we highlight the main findings of every paper while offering insights into the common themes of the rate optimization methods in each category. Finally, we offer future research directions for each of these NOMA integrated schemes.

A. Related Work and Existing Surveys

The up-to-date list of surveys [1]–[3], [12]–[26] and magazine articles [27]–[51] that have appeared on PD-NOMA schemes are shown in Table I. As the table captures, many of these survey papers go beyond the typical NOMA setting and discuss the integration with multiple antennas and other technologies. Of these, the paper in [12] is the most related in looking into the interplay between NOMA and other emerging technologies. However, we differentiate our survey from the work in [12] and others by focusing on the rate-optimization problems that arise from the integration of these technologies with NOMA schemes. As discussed before in this Section, the central theme of this survey surrounds the system models, design objectives, constraints, etc. involved in solving the typically non-convex rate optimization problems that arise from the integration of the system parameters of both NOMA and the other enabling technologies. In this way, we distinguish our work from [12] which is a more general discussion of how NOMA enables these other technologies. Some other surveys identified in Table I discuss rate-optimal NOMA schemes in certain settings or with some enabling technologies. However, to the best of the authors’ knowledge, no survey exists today that is dedicated to the investigation of the optimization of PD-NOMA schemes with the main PHY-layer enabling technologies and schemes for high data rate future communication networks.

It is also worth highlighting that achievable rate optimization problems form the vast majority of existing work in these NOMA integrated enabling 5G schemes studied in the literature. Hence, we limit the scope of the survey to the rate optimization problems to ensure a good focus for the discussion, but it still captures a vast majority of the work in this area. As a result, papers that investigated other performance analyses metrics such as symbol error rate (SER), bit error rate (BER), and outage probability in such PD-NOMA integrated schemes are beyond the scope of this survey. The interested reader may refer, for example, to the work published

1 In this paper, we refer to NOMA and PD-NOMA interchangeably. Hence, where NOMA is used after this point, it always refers to the PD-NOMA.
TABLE I: A comprehensive taxonomy of the integration of PD-NOMA schemes with some of the future emerging communication systems in existing surveys and magazine papers.

| Reference | Year | Type       | MIMO and mMIMO | CoMP | Cooperative Communication | Cognitive Radio | mmWave | VLC | UAV | V2X |
|-----------|------|------------|----------------|------|--------------------------|-----------------|--------|-----|-----|-----|
| [13]      | 2016 |            |                 | ✓    | ✓                       |                 |        |     |     |     |
| [14]      | 2016 |            |                 | ✓    | ✓                       |                 |        |     |     |     |
| [15]      | 2017 |            |                 | ✓    | ✓                       |                 |        |     |     |     |
| [16]      | 2017 |            |                 | ✓    | ✓                       |                 |        |     |     |     |
| [17]      | 2017 |            |                 | ✓    | ✓                       |                 |        |     |     |     |
| [1]       | 2017 |            |                 | ✓    | ✓                       |                 |        |     |     |     |
| [2]       | 2018 |            |                 | ✓    | ✓                       |                 |        |     |     |     |
| [3]       | 2018 |            |                 | ✓    | ✓                       |                 |        |     |     |     |
| [18]      | 2018 |            |                 | ✓    | ✓                       |                 |        |     |     |     |
| [19]      | 2018 |            |                 | ✓    | ✓                       |                 |        |     |     |     |
| [20]      | 2018 |            |                 | ✓    | ✓                       |                 |        |     |     |     |
| [21]      | 2018 |            |                 | ✓    | ✓                       |                 |        |     |     |     |
| [22]      | 2018 |            |                 | ✓    | ✓                       |                 |        |     |     |     |
| [23]      | 2018 |            |                 | ✓    | ✓                       |                 |        |     |     |     |
| [24]      | 2018 |            |                 | ✓    | ✓                       |                 |        |     |     |     |
| [12]      | 2019 |            |                 | ✓    | ✓                       |                 |        |     |     |     |
| [25]      | 2019 |            |                 | ✓    | ✓                       |                 |        |     |     |     |
| [26]      | 2019 |            |                 | ✓    | ✓                       |                 |        |     |     |     |
| [27]      | 2015 |            |                 | ✓    | ✓                       |                 |        |     |     |     |
| [28]      | 2015 |            |                 | ✓    | ✓                       |                 |        |     |     |     |
| [29]      | 2017 |            |                 | ✓    | ✓                       |                 |        |     |     |     |
| [30]      | 2017 |            |                 | ✓    | ✓                       |                 |        |     |     |     |
| [31]      | 2017 |            |                 | ✓    | ✓                       |                 |        |     |     |     |
| [32]      | 2017 |            |                 | ✓    | ✓                       |                 |        |     |     |     |
| [33]      | 2017 |            |                 | ✓    | ✓                       |                 |        |     |     |     |
| [34]      | 2018 |            |                 | ✓    | ✓                       |                 |        |     |     |     |
| [35]      | 2018 |            |                 | ✓    | ✓                       |                 |        |     |     |     |
| [36]      | 2018 |            |                 | ✓    | ✓                       |                 |        |     |     |     |
| [37]      | 2018 |            |                 | ✓    | ✓                       |                 |        |     |     |     |
| [38]      | 2018 |            |                 | ✓    | ✓                       |                 |        |     |     |     |
| [39]      | 2018 |            |                 | ✓    | ✓                       |                 |        |     |     |     |
| [40]      | 2018 |            |                 | ✓    | ✓                       |                 |        |     |     |     |
| [41]      | 2018 |            |                 | ✓    | ✓                       |                 |        |     |     |     |
| [42]      | 2018 |            |                 | ✓    | ✓                       |                 |        |     |     |     |
| [43]      | 2018 |            |                 | ✓    | ✓                       |                 |        |     |     |     |
| [44]      | 2018 |            |                 | ✓    | ✓                       |                 |        |     |     |     |
| [45]      | 2018 |            |                 | ✓    | ✓                       |                 |        |     |     |     |
| [46]      | 2018 |            |                 | ✓    | ✓                       |                 |        |     |     |     |
| [47]      | 2018 |            |                 | ✓    | ✓                       |                 |        |     |     |     |
| [48]      | 2019 |            |                 | ✓    | ✓                       |                 |        |     |     |     |
| [49]      | 2019 |            |                 | ✓    | ✓                       |                 |        |     |     |     |
| [50]      | 2019 |            |                 | ✓    | ✓                       |                 |        |     |     |     |
| [51]      | 2019 |            |                 | ✓    | ✓                       |                 |        |     |     |     |

Survey Papers

Magazine Articles

This survey paper

in [52]–[55] and references therein to explore the performance of PD-NOMA schemes for the aforementioned metrics. In addition, works that investigated the power minimization, for example, [56]–[59], the maximization of secrecy rate, for example, [60]–[63], and the maximization of energy efficiency, for example, [64]–[66] in PD-NOMA schemes are also beyond the scope of this survey paper.

B. Paper Organization

The organization of this paper is as follows. In Section II, we first provide a brief description of PD-NOMA itself, followed by a description of the main enabling communication schemes and technologies in current and future wireless networks that are discussed in this paper. Section III surveys the integration of PD-NOMA schemes with these enabling schemes, namely MIMO/mMIMO, mmWave, CoMP, cooperative communication, cognitive radio, VLC, and UAV communications. In Section IV, we provide a list of possible directions for future research for each of the aforementioned technologies and their combinations. Also, the list of abbreviations used in this survey paper is presented in Table II.
TABLE II: The list of abbreviations.

| Abbreviation | Description |
|--------------|-------------|
| 3GPP         | 3rd generation partnership project |
| 5G           | Fifth generation |
| AP           | Amplify-and-forward |
| AO           | Alternating optimization |
| AP           | Access point |
| BSG          | Beyond fifth generation |
| BA           | Bisection algorithm |
| BCD          | Block coordinate descent method |
| BF           | Beamforming |
| BS           | Base station |
| CB           | Coordinated beamforming |
| CP           | Compress-and-forward |
| CgMP         | Coordinated multi-point |
| CR           | Cognitive radio |
| CSI          | Channel state information |
| CSIT         | Channel state information at the transmitter |
| D.C.         | Difference of convex |
| D2D          | Device-to-device |
| DF           | Decode-and-forward |
| FD           | Full-duplex |
| DL           | Downlink |
| FoV          | Field of view |
| FPA          | Fixed power allocation |
| Gf           | Geometric program |
| GPA          | Gradient projection algorithm |
| GRPA         | Gain ratio power allocation |
| HAP          | High altitude platform |
| HD           | Half-duplex |
| Het-nets     | Heterogeneous networks |
| ICI          | Inter-cell interference |
| JT           | Joint Transmission |
| KKT          | Karush-Kuhn-Tucker |
| LAP          | Low altitude platform |
| LED          | Light emitting diode |
| LoS          | Line-of-sight |
| LTE-A        | Long term evolution advanced |
| MIMO         | Multiple-input-multiple-output |
| MISO         | Multiple-input-single-output |
| MMMA         | Minimization maximization algorithm |
| mMIMO        | Massive multiple-input-multiple-output |
| mMTC         | Massive machine type communications |
| mmWave       | Millimeter-wave |
| MU-MIMO      | Multi-user multiple-input-multiple-output |
| NGdPA        | Normalized gain difference power allocation |
| NOMA         | Non-orthogonal multiple access |
| NR           | New radio |
| OFDMA        | orthogonal frequency division multiplexing access |
| OMA          | Orthogonal multiple access |
| PA           | Power allocation |
| PD-NOMA      | Power domain NOMA |
| PHY          | Physical layer |
| PU           | Primary user or licensed user |
| RF           | Radio frequency |
| SCA          | Sequential convex approximation |
| SCMA         | Sparse code multiple access |
| SDMA         | Spatial division multiple access |
| SDP          | Semi-definite programming |
| SDR          | Semi-definite relaxation |
| SE           | Spectral efficiency |
| SIC          | Successive interference cancellation |
| SINR         | Signal-to-noise and interference ratio |
| SISO         | Single-input-single-output |
| SNR          | Signal-to-noise ratio |
| SU           | Secondary user or non-licensed user |
| SWIPT        | Simultaneous wireless information and power transfer |
| TPs          | Transmission points |
| TRPs         | Transmission reception points |
| UAV          | Unmanned aerial vehicle |
| UL           | Uplink |
| US           | User selection |
| V2V          | vehicle-to-vehicle communication |
| V2I          | vehicle-to-infrastructure communication |
| V2X          | Vehicle-to-everything communication subsumes vehicle-to-vehicle and vehicle-to-infrastructure communications |
| VLC          | Visible light communications |
| WMMSE        | Weighted minimum mean square error |
| ZF           | Zero-forcing |

II. BACKGROUND

In this section, a brief introduction to PD-NOMA schemes as well as to some of the main PHY-layer enabling technologies and schemes for future communication networks is presented. The objective of this section is to familiarize the reader with the fundamentals of each of these communications technologies or schemes. Hence, relevant references are provided in each sub-section where further details about each technology or scheme can be found.

A. Power Domain NOMA Schemes

Power-domain NOMA concept was first introduced in [67] to improve the spectral efficiency of wireless networks by allowing multiple users to simultaneously share both the time and frequency resources. The theoretical roots of PD-NOMA schemes lie in multi-user information theory. These include scalar and vector multiple access and broadcast channels along with the superposition coding, successive interference cancellation (SIC), joint decoding, iterative water-filling, dirty paper coding, and other related transmission and reception schemes [16]. However, NOMA schemes add additional "comm-theoretic" constraints on the users’ target rates, in addition to the typical transmit power constraint in the info-theoretic models, to guarantee the fairness among the served users.

A basic two-user downlink (DL) NOMA scheme is shown in Fig. 1. User 1 (strong user) is close to the BS with strong channel gain and User 2 (weak user) is farther away from the BS with weaker channel gain. At the transmitter, both signals for the weak and the strong users are superimposed upon each other with different power allocation. The transmitter tends to allocate more power to the weak user as it has a larger path loss, as compared to the strong user (note that the size of the rectangles for User 1 and User 2 are different indicating the different powers allocated for each user). At the strong user receiver, the signal of the weak user has high signal-to-noise ratio (SNR) which implies that the strong user can successfully decode and subtract the weak user signal before decoding its own signal (i.e., performing SIC). On the other hand, at the weak user receiver, the strong user signal is considered as noise as its transmission power is lower than the weak user signal. Subsequently, the weak user can decode its signal directly without SIC [68]. In a basic two-user uplink (UL) NOMA scheme, both users transmit their signals to the BS simultaneously (i.e., in the same time slot and frequency channel). For practical reasons [34], both users need to have some sort of cooperation to transmit both signals under a total transmit power constraint. The power share of both users is distributed based on their channel conditions with respect to the BS. After the transmission process, the BS receives a superimposed signal that contains both users’ signals. Subsequently, the BS performs SIC with a decoding order from the strongest user to the weakest user to decode both individual users’ signals. Noting that SIC capability is already incorporated in earlier wireless standard such as network-assisted interference cancellation and suppression (NAICS) in LTE (3GPP release 12) [69].
The grouping or clustering of the users to be served in the same resource block is essential in NOMA schemes and is typically carried out as two users per cluster (also known as user pairing) or multiple users per cluster. The selection in basic NOMA schemes, with single-antenna BS/access point (AP) and single-antenna users, is usually based on the instantaneous scalar channel gains and the users are ranked accordingly to allow proper SIC decoding which tends to improve as the channel gain disparity increases unless the channel gain of the weaker user is very small which may render NOMA inefficient. In general, the optimal user clustering requires an exhaustive search and may not be affordable for practical systems and networks with a large number of users [70]. For this reason, researchers resort to low complexity solutions to solve the user clustering problem through heuristic algorithms which may lead to unpredictable results.

Alternatively, the other approaches for handling the NOMA clustering problem are [16]:

- The monotonic optimization approach as in [71]; the monotonic nature of the objective function and constraints allows researchers to limit the exhaustive search to a much smaller region of the feasible set; this accordingly simplifies the problem and can lead to the optimal solution but still with relatively high complexity.

- The combinatorial relaxation approach; the selection and association of a particular user to a particular cluster is realized by a binary variable; by relaxing this variable to a continuous one, the original non-convex problem can be transformed to a convex one and solved optimally through classic Lagrangian dual method [72], but this relaxation results in a performance gap between the original problem and the relaxed one.

- The matching theory approach: which is often utilized to deal with problems that have beneficial relationship parties, such as the many-to-one bipartite matching problem [73], the many-to-one two-sided matching problem [74], and, the many-to-many two-sided matching problem [75], [76].

- The game theory approaches; which transform the clustering problem to a game, such as the coalition game and improved coalition game proposed in [77]–[79] and in [80], respectively, and the Stackelberg game proposed in [81].

Early work on PD-NOMA schemes started with basic single-cell scenarios, and then evolved to multi-cell and multi-carrier scenarios. Recently, NOMA schemes have been integrated with more practical and sophisticated system models alongside other promising communication technologies and schemes to meet the target performance of future wireless networks.

B. MIMO, mMIMO, and mmWave Systems

MIMO, and particularly massive-MIMO (mMIMO), has already emerged as a key technology enabler in 5G cellular systems [82], [83]. The MIMO technology exploits the multiple antennas available at the transmitter, receiver, or at both ends of the communication system. If there are multiple antennas only at the transmitter, and not at the receiver, these are referred to as multiple-input-single-output (MISO) systems. The multiple antennas in a MISO or MIMO system can be used in several ways. In a point-to-point scenario, they can be used to achieve a diversity gain through beamforming or, in a MIMO system, they can be used to achieve a spatial multiplexing gain [84].

In a multi-user environment, the multiple antennas can be used to separate the users in the space domain, creating the so-called spatial division multiple access [84]. Such a separation in space is achieved through the use of large-scale antenna arrays at the BS. The placement of antennas in these antenna arrays can be used to achieve 2-D separation of users in the azimuth plane, e.g., through a uniform linear array (ULA), or alternatively for 3-D separation of users in both the azimuth and vertical direction, sometimes called 3-D MIMO [85]. Furthermore, if the number of transmit antennas far exceeds the number of users in the system, it is often referred to as a large-scale or massive multi-user MIMO system. In such mMIMO systems, when the number...
of transmit antennas approach infinity, it creates the favorable propagation conditions whereby a unique beam can be formed for each user and perfect separation in the space domain is possible [86].

A closely related enabler of 5G and beyond cellular networks is mmWave communications [87], which operate in the frequency range of 30-300 GHz. In contrast to the sub-6 GHz frequency range, a large amount of bandwidth is available in the mmWave spectrum. Hence, mmWave communication is seen as a key enabler of high data rates in future cellular networks. However, unlike in the sub-6 GHz spectrum, the propagation of electromagnetic waves in the mmWave bands experience high path loss and is highly directional in nature [74]. As a result, the beam gain offered by large-scale antenna arrays, i.e., mMIMO systems, is seen as a requirement to enable successful deployment of networks in these high-frequency bands [88]. Additionally, the short wavelengths of the electromagnetic waves in the mmWave frequency band make it practical to deploy large antenna arrays in a compact area, as required by a massive-MIMO system [89].

C. Coordinated Multi-Point (CoMP) Schemes

The practical considerations in interference-limited heterogeneous multi-cellular environments as well as the promising info-theoretic benchmarks, where a network with fully cooperating cells reduces to a simple broadcast channel, have led to the introduction of network cooperation schemes known as network MIMO or CoMP schemes. This is to allow the base stations or the access points to cooperate in order to mitigate or reduce the inter-cell interference (ICI) and to enhance the received signal quality [90], [91]. The degree of cooperation may vary depending on the availability of users’ data and/or the channel state information (CSI) as itemized below:

- Both the users’ data and CSI are available at all the transmission and reception points (TRPs). This availability enables full joint coordination or processing. Here, the cooperating BSs or APs (also known as transmission points (TPs) or TRPs or CoMP-cells) jointly transmit to the served users (typically the cell-edge users) or TP selection where only one or a subset of the cooperating TPs, usually the TP with the highest received signal-to-noise and interference ratio (SINR), sends to the desired user(s).
- Only the CSI is available at all the TRPs. This relaxed and less-demanding requirement of having only the CSI at the cooperating TPs allows reducing ICI through coordinated scheduling of the users and joint beamforming.

As can be seen, the TP selection and coordinated beamforming schemes are less complex. This is primarily because of its less overhead requirement, less stringent requirement on backhaul performance, and less synchronization requirements, as compared to the full joint coordination scheme. Moreover, different requirements or priorities by the operators would lead to different CoMP implementations such as cell-centric, user-centric and hybrid clustering algorithms [91].

Early deployment of CoMP was in 3GPP LTE-A standard where all the CoMP variants above were investigated and evaluated [92]. In B5G (beyond 5G) networks, the ultra-dense deployment of small cells or small BSs in heterogeneous ultradense cellular networks would result in more of both co-tier and cross-tier inter-cell interferences and hand-off requests which necessitates the use of CoMP schemes to enable “cell-less” networks and to efficiently combat the inter-cell interference and improve network performance especially for cell-edge users.

D. Cooperative Communication Systems

Cooperative communication systems allow some communication terminals in the network to interact with each other for the sake of improving reliability, enhancing spectrum efficiency as well as power efficiency, and, improving network connectivity by taking advantage of the broadcast nature of the wireless links [94].

There are three possible ways to realize the cooperation between the nodes in the network; (i) by allowing the communication terminals to hear-and-forward messages to other terminals, (ii) by using an extra relaying node to help in information and/or energy transfer between the source(s) and their corresponding destination(s), and, (iii) by allowing some user pair(s/group(s) to interchange signals without traversing the BS or the core network. The first type of cooperation is often referred to as user-assisted communication, the second is often referred to as relay-assisted communication, and, the third type is often referred to as device-to-device (D2D) communication [95], [96].

D2D communication systems can be considered as an enabler for vehicle-to-everything (V2X) applications. In 3GPP Release 14, an initial cellular V2X standard has been completed as a part of expanding LTE platform to new services [97]. Later in 3GPP Release 15, in V2X phase 2, some service requirements to enhance the support for V2X scenarios have been identified [98]. In 3GPP Release 16, in NR-V2X, further architecture enhancements to the 5G system have been specified in order to facilitate vehicular communications for V2X services [99]. In 3GPP Release 17, some enhancements to the application architecture to support V2X services have been specified [100]. In V2X applications, vehicles have the ability to exchange data with each other and with the infrastructure/network units. The former is often referred to as vehicle-to-vehicle (V2V) communication and the later is often referred to as vehicle-to-infrastructure (V2I) communication.

In addition to the above, there are two types of relaying strategies, namely, half-duplex and full-duplex. If the system works under the half-duplex strategy, then the system will operate in two phases, where in the first phase, the BSs or APs broadcast the signals to the nearby receivers (i.e., users/relays). Consequently, in the second stage, the nearby receivers forward the messages of far receivers. On the other hand, if the system works under a full-duplex relaying strategy, then the relays/users node will simultaneously receive and forward the signals to their intended destinations. Although full-duplex technology introduces some self-interference (SI) caused by the signal leakage from the transceiver output to the input [101], which degrades the performance of the full-duplex
system, still full-duplex technology has the capability of utilizing the total bandwidth of the system as it hears-and-forwards the signals on the same frequency. Recent advancements in SI cancellation technologies and the move towards short-range networks such as small-cell cellular networks, which have lower path loss than that on the traditional cellular networks, have reduced the severity of SI and paved the way for full-duplex technology to be an emerging technique for future wireless networks [102].

Moreover, there are three main relaying protocols: (i) decode-and-forward (DF) relaying, (ii) amplify-and-forward (AF) relaying, and (iii) compress-and-forward (CF) relaying. In DF relaying protocol, the received signal is completely decoded and then re-encoded and sent to the intended receiver(s). In AF relaying protocol, the received signal with its embedded noise is amplified and forwarded to the designated receiver. While in CF relaying protocol, the relay quantizes/compresses the overheard signal and then sends the resultant signal to the designated receiver [19].

E. Cognitive Radio Communication Systems

Most of the radio spectrum has been allocated to certain wireless applications because of its increasing demand, and the need for more bandwidth for new applications. The Federal Communications Commission (FCC) reported that the utilization of this allocated spectrum varies from 15% to 85% with high variance in time and space [103] and cognitive radio (CR) idea appeared as a proposed solution for the low spectrum utilization problem [104]. The main idea of CR depends on enhancing the utilization of the pre-allocated spectrum through allowing the non-licensed users (SUs) to coexist with primary users (PUs) or exploit the white spaces of the spectrum in the absence of PUs [105].

CR schemes can be classified into three paradigms, namely, underlay, overlay, and interweave [106]. In the underlay CR paradigm, the SUs are allowed to access the PUs networks as long as the interference power constraint of the PU is not violated [107]. While in the overlay CR paradigm, the PUs and SUs are capable of transmitting signals simultaneously. In this paradigm, the PUs’ SNR will be affected by an interference caused by the SUs’ transmission, in order to compensate for that decrease in the PUs’ SNR, the SUs is forced to split their transmission power between secondary transmission and the remaining power is used to relay (assist) primary transmissions [108]. Furthermore, in the interweave CR paradigm, the SUs are allowed to utilize the channel(s) only if not occupied by the PUs. Note that, the interweave CR paradigm does not authorize any concurrent transmission between SUs and PUs, hence it is known to be an interference-limited spectrum sharing mode [109].

F. Visible Light Communications (VLC) Systems

Visible light communications (VLC) has recently emerged as a potential technology for complementing and/or off-loading radio frequency (RF) communication systems for various indoor user-dense scenarios such as homes, office rooms, conference and exhibition halls, airplanes and train cabins as well as some outdoor and V2X applications in 5G and 6G networks. VLC is based on the principle of modulating light emitted by diodes (LEDs), without any adverse effects on the human eye and the required illumination levels, which gives an opportunity to exploit the existing illumination infrastructure for wireless communication purposes.

A generic model for a multi-user VLC system is shown in Fig. 2 where a set of transmit \( N_t \) LEDs communicate with a set of users. This is a typical indoor downlink scenario where the LEDs on the ceiling transmit the downlink data to the VLC receivers that are typically equipped with photodetectors [110]. The field of view (FoV) of the LEDs and the photodiodes are designed to satisfy both the illumination and communication requirements. Each shaded area represents the interference or overlap region imposed by the signals carrying different information and arriving from the neighboring LEDs. While there is negligible signal fading experienced in VLC channels, the SINR significantly drops at the boundary of interference region and by obstruction of the line-of-sight (LoS) path due to user mobility.
Fig. 3: A generic UAV system model where the UAV acts as a flying BS and jointly serves users along with a ground BS.

G. Unmanned Aerial Vehicle (UAV) Assisted Communication Systems

UAV-assisted communication networks is an emerging paradigm in the beyond 5G (B5G) wireless networks to support high transmission rates, to provide ubiquitous connectivity to a diverse set of end-users, and, to facilitate wireless broadcast [23], [111], [112]. UAV can play several roles in this paradigm, e.g., act as a flying BS, a relay in flying ad-hoc networks or even as user equipment (UE) [113]. The UAVs can be deployed as a high altitude platform (HAP) for long-term use or as a low altitude platform (LAP) for fast and flexible deployment when used as a BS [113], [114].

We now focus on the use-case where the UAV acts as a LAP BS to serve users in an ad-hoc manner. This is illustrated in Fig. 3, where the UAV complements the ground BS and serves some users in conjunction with the ground BS. The main idea in this type of deployment is to bring the supply of wireless networks to where the demand is in both space and time, acting as a complement to the terrestrial communication network [115]. As illustrated in Fig. 3, like in any multi-cell network, the UAV will cause interference to the users served by the ground BS and vice-versa. However, the problem can be addressed with additional degrees of freedom that a flying BS allows which does not exist in traditional terrestrial BSs. These include designing the height and placement of the UAV BS and the high probability of LoS links between the UAV and the served users [23].

III. PD-NOMA SCHEMES IN ENABLING SCHEMES/TECHNOLOGIES IN FUTURE WIRELESS NETWORKS

In this part of the paper, a survey on the integration of PD-NOMA schemes with MIMO/mMIMO, mmWave, CoMP, cooperative, cognitive radio, VLC, and UAV communications is conducted through the up-to-date lists provided in Table III to Table IX, of the representative work for each of the aforementioned schemes and technologies.

A. Rate-optimal NOMA Schemes in MIMO, mMIMO, and mmWave Systems

The representative work on MISO, MIMO, and mMIMO integrated NOMA systems are presented in Table III and Table IV for both the single-cell and multi-cell scenarios. Compared to the basic single-input-single-output NOMA (SISO-NOMA) system described in Section II-A, the use of multiple antennas at either the transmitter, receiver, or both means that the channel is now described by a vector or a matrix. Hence, unlike in a SISO-NOMA system, the ordering of users according to their channel conditions is no longer trivial. This is typically achieved by using the multiple antennas at the transmitter for beamforming, such that users can be grouped into beams, often referred to as clusters. Within each cluster, the problem breaks down into a typical SISO-NOMA setting and the traditional PD-NOMA scheme as described in Section II-A can be used. This approach is classified as NOMA-BF in [30] and cluster-based MIMO-NOMA in [16]. Alternatively, the multiple antennas at the base station can also be used to form one beam per user like in MU-MIMO, and then the beamforming weights are designed to create enough difference between the users’ channel conditions such that the NOMA principles can be applied [123].

With the clustering-based approach, the two users should have sufficient difference in the magnitude of the channel gain coefficients for PD-NOMA schemes to work well [1]. Thus, user selection (US) is a key parameter in such schemes. The objective here is to pair users who have sufficiently different channel conditions and also fit within a cluster, i.e., a beam. This design variable (or parameter) is often optimized in such schemes along with the PA coefficients assigned to each user in the cluster, e.g., [34], [117]. However, with randomly located users, good user pairing algorithms are not guaranteed to find the ideal user clustering even with an exhaustive search of all possible solutions [156] because acceptable solutions may not exist. Hence, user-specific beamforming weights are also considered as a parameter in these sum-rate optimization problems [119], [122], [134], [156], [157]. The addition of the
### TABLE III: MISO-NOMA and MIMO-NOMA systems: current status of rate optimization schemes.

| References | Classification | System Model | Design Objective | Optimization Method | Main Finding(s) |
|------------|----------------|--------------|-----------------|-------------------|-----------------|
| **MISO**  | Two users only | One BS + two users | Max. ergodic sum-rate | Gradient projection algorithm (GPA) and Bisection algorithm (BA) | The proposed schemes outperform OMA and SDMA in the two-user scenario |
| [116]     |                | One BS + K users (Two users per cluster) | Max. sum rate | Iterative clustering and power allocation algorithm | The proposed scheme outperforms traditional MU-MIMO for the setting where two correlated users per cluster are available |
| [117]     | Multiple users with clustering | One BS + K users (Two users per cluster) | Max. sum rate | Geometric programming (GP), then successive optimization to find Karush-Kuhn-Tucker (KKT) point | Applying ZF-BF in a MIMO-NOMA setup with two users per cluster maximizes the sum rate of the users in the cluster |
| [118]     |                | One BS + K users (Two users per cluster) | Max. sum rate | Pareto-boundary computed using reformulation and convex-concave procedure (Maxmin user-rate) | The proposed scheme allows for rate control between strong and weak users, offering flexibility compared to other MISO-NOMA schemes |
| [119]     |                | One BS + K users (Two users per cluster) | Max. sum rate | Branch-and-bound (BnB) method | NOMA with the proposed BnB technique for beam design outperforms NOMA with ZF |
| [120]     |                | One BS + K users uniformly distributed around the BS | Max. ergodic sum rate | One dimensional search | Proposed scheme optimizes the number of feedback bits, but a performance gap always exists compared to the perfect CSI case. |
| [121]     |                | One BS + K users | Max. worst-case sum rate | Alternating optimization (AO) method | The proposed scheme optimizes the worst-case achievable sum-rate through robust BF design & outperforms OMA |
| [122]     | One beam per user (user ordering assumed) | One BS + K users | Max. sum rate | Minimization maximization algorithm (MMA) | The proposed algorithm applies user-specific precoding and the algorithm is shown to converge in a few iterations |
| [123]     |                | One BS + K users | Max. weighted sum rate | KKT optimality conditions (hidden convexity for homogeneous channels) | The proposed algorithm designs user-specific beam weights by exploiting favorable complexity in the NOMA WSR problem |
| [124]     | Other | Multiple groups each getting multi-cast data | Max. sum rate | Bisection with Majorization-Minimization algorithm | The proposed scheme always performs better than OMA, but performs better than SDMA only in select scenarios |
| [125]     | An UL system with one BS + K users, SIC is applied at the codeword-level | Multiple BS users | Maximized weighted average SINR | Geometric programming (GP) | The proposed scheme mitigates the error propagation problem specific to UL MIMO-NOMA systems |
| [126]     | K users in C groups (Groups based on channel gain) | One BS + K users | Max. sum rate | Singular value decomposition based multi-user scheme that exploits CSI | The proposed scheme has lower complexity than the MMA scheme in [123] and the duality scheme in [125] |
| [127]     |                | One BS + two users | Max. sum rate | Bisector and heuristics algorithms. | The sum rate - complexity tradeoff was analysed and the proposed heuristics achieved a good balance |
| **MIMO**  | Two users only | One BS + two users | Max. ergodic capacity | Bisection algorithm (with sub-optimal bounds) | The proposed scheme is superior to MIMO-OMA scheme for each user |
| [128]     |                | One BS + two users | Max. sum rate and Max. average sum rate | Alternating optimization (AO) method | Sum rate in MIMO-NOMA system with layer transmission is concave in allocated powers to the multiple layers |
| [129]     |                | One BS + two users | Max. average sum rate | Lagrangian dual decomposition | The proposed scheme adapted power and rate allocation to the channel fading state |
| [130]     |                | One BS + two users | Max. sum rate | Bisection algorithm | Sum rate in the proposed scheme is better than TDMA MIMO and MU-MIMO for the 2-user scenario studied |
| [131]     | Multiple users with clustering | One BS + K users (Two users per cluster) | Max. weighted sum rate | Iterative weighted minimum mean square error (WMMSE) algorithm | The proposed scheme outperforms a ZF-precoder for this system model |
| [132]     |                | One BS + K users (num. antennas at UE > num.antennas at BS) | Max. sum rate | Sub-optimal heuristics | The proposed scheme uses long-term channel feedback for US, but the instantaneous CSI for beam design and this outperforms traditional MU-MIMO |
| [133]     |                | One BS + K users (short + long-term channel feedback) | Max. weighted sum rate | Iterative WMMSE algorithm | The proposed scheme outperforms the US and power allocation (PA) scheme performs better than OMA and other MIMO-NOMA schemes for this antenna configuration |
| [134]     | One beam per user | One BS + K users (with channel uncertainties) | Max. worst case achievable rate | Cutting-set method WMMSE formulation | The proposed robust design is shown to handle channel uncertainties better than a non-robust design |
| [135]     | Other | One BS + K users (using a specialized superposition scheme) | Max. sum rate | Convex optimization problem solved with interior-point method | The proposed superposition scheme does not affect the decoding of signalling info, allowing for sum-rate gains |
| [136]     | Multi-cell | Multi-antenna users (Two users per cluster) | Max. sum rate | Convex quadratic programming and semi-definite programming (SDP) | The proposed path-following algorithms increase the overall sum-rate in the system compared to any OMA scheme |
| [137]     |                | Multi-antenna users and a two-cell setup with no CoMP | Max. weighted sum rate of strong user in each cell | Segregated convex approximation (SCA) and MMA techniques | The proposed segregated convex approximation is superior to ZF-NOMA, orthogonal NOMA and OMA schemes |
| [138]     | Single-antenna users (No clustering) | One BS + K users | Max. sum rate | Iterative scheme based on local optimum till KKT optimality conditions are satisfied | NOMA with the proposed PA scheme achieves higher sum-rate than NOMA schemes with basic PA |
| [139]     | MIMO-NOMA scheme | One BS + K users | Max. sum rate | A game theory based approach | The proposed scheme achieves better system sum-rate performance compared to conventional MIMO-OMA and MIMO-NOMA based HetNets schemes |
TABLE IV: mMIMO-NOMA and mmWave-NOMA systems: current status of rate optimization schemes.

| References | Classification | System Model | Design Objective | Optimization Method | Main Finding(s) |
|------------|----------------|--------------|------------------|---------------------|----------------|
| [142]      | mMIMO BS       | single-antenna users | Max. sum rate | Heuristic PA algorithm | A user pairing algorithm with the proposed hybrid approach outperforms traditional MU-MIMO in scenarios with correlated users. |
| [143]      | mMIMO BS       | single-antenna users Clustering-based | Max. weighted sum rate | SCA technique | With the proposed PA scheme, NOMA achieves significant spectral efficiency (SE) gain in massive connectivity scenarios. |
| [144]      | mMIMO BS       | multi-antenna users | Max. sum rate | Heuristic US algorithm | The proposed US algorithm enhances the sum rate compared to other US algorithms that group pairs of users. |
| [145]      | mMIMO BS       | A single-antenna users with the frequency resource split into K subbands, with two users paired in one subband. | Max. sum rate | Exhaustive search and sub-optimal heuristic algorithms | The proposed sub-optimal antenna selection and US algorithms perform similar to other schemes, but at reduced complexity. |
| [146]      | An UL system with a mMIMO BS that performs antenna selection. | Max. sum rate | Exhaustive search and sub-optimal heuristic algorithms | The proposed US, PA and antenna selection scheme outperforms MU-MIMO and other MIMO-NOMA schemes in terms of sum rate. |
| [147]      | Multi-cell mMIMO BSs | Max. sum rate | Geometric programming, then Successive Approximation | The proposed scheme works better than OMA and other MIMO-NOMA schemes in massive connectivity scenarios. |
| [148]      | A two-tap Het-nets cooperative multicast mmWave NOMA scheme, K multi-antenna users | Max. sum rate | A golden section search algorithm | The proposed cooperative NOMA multicast outperforms NOMA multicast and in terms of the sum multicast rate. |
| [149]      | A beamspace mMIMO-NOMA scheme in mmWave band, K single-antenna users | Max. sum rate | An iterative optimization algorithm | The proposed scheme can achieve higher spectrum efficiency than that of beamspace MIMO scheme. |
| [73]       | A random beamforming mmWave NOMA scheme, K single-antenna users | Max. sum rate | A suboptimal algorithm based on matching theory | The proposed scheme outperforms the conventional mmWave OMA scheme in terms of the sum rate. |
| [150]      | An uplink mmWave NOMA scheme, two single-antenna users | Max. sum rate | A suboptimal solution via decomposing and relaxing the original non-convex problem | The proposed scheme achieves better sum rate performance as compared to OMA scheme. |
| [81]       | A downlink mmWave-NOMA scheme, single-antenna users | Max. sum rate | A game theory based algorithm | The proposed scheme outperforms the conventional mmWave-OMA scheme in terms of the sum rate. |
| [151]      | A downlink mmWave-NOMA scheme, single-antenna users | Max. sum rate | A K-means based machine learning algorithm | The proposed scheme outperforms the mmWave-NOMA scheme with random-user clustering and its counterpart mmWave-OMA scheme in terms of the sum rate. |
| [152]      | A hybrid precoding-based MIMO-NOMA scheme with SWIPT, single-antenna users | Max. sum rate | Iterative optimization algorithm | The proposed scheme achieves higher sum rate than a hybrid-based MIMO-OMA scheme with SWIPT. |
| [153]      | A multi-beam mmWave NOMA scheme, K multi-antenna users | Max. sum rate | Difference of convex (D.C.) programming transformation | The proposed scheme provide a higher sum-rate performance as compared to the single-beam mmWave-NOMA and mmWave-OMA schemes. |
| [74]       | A downlink mmWave mMIMO-NOMA scheme with hybrid architecture, single-antenna users | Max. sum rate | A matching theory based algorithm and an iterative optimization algorithm | The proposed scheme provide a higher sum-rate performance as compared to the conventional beamspace MIMO scheme. |
| [89]       | A downlink mmWave-NOMA scheme with analog beamforming, single-antenna users | Max. sum rate | A suboptimal solution via decomposing and relaxing the original non-convex problem | The proposed scheme provide a higher minimal-user rate performance as compared to the conventional mmWave-OMA scheme. |
| [154]      | A downlink mmWave-NOMA scheme, single-antenna users, Hybrid BF and user clusters formed | Max. sum rate | Sub-optimal heuristics | The proposed joint UP-Hybrid BF PA scheme outperforms the conventional mmWave-OMA systems and the mmWave-NOMA scheme in [152]. |
| [155]      | A downlink mmWave-NOMA scheme, K users, analog phased arrays at BS & users | Max. sum rate | Sub-optimal heuristics | The proposed scheme outperforms mmWave-OMA and the scheme proposed by the same authors in [155]. |

optimization of the per-user BF weights to the clustering-based MIMO-NOMA rate optimization problem allows the schemes to either create more channel gain difference among the users in a cluster, or to better separate the different clusters from each other.

With the one-beam-per-user model, the user ordering is predefined and the optimization schemes design a set of precoder weights to meet the given user ordering [123], [124]. The sum rate of the users is maximized through a minorization maximization algorithm (MMA) for the non-convex problem proposed by Hanif et al. [123]; while in the technique suggested by Zhu et al. [124] it is shown that forming a weighted sum-rate maximization problem instead has hidden convexity that can be solved using the KKT optimality conditions. While this one-beam-per-user approach generally requires full channel state information at the transmitter (CSIT) for the required beamforming design, the study in [136] framed an optimization problem to maximize the worst-case achievable rate in order to offer robustness to channel uncertainties.

The availability of CSIT also affects the formulation of the MIMO-NOMA rate optimization problems considered in the literature. If the full CSIT is available, the design objective...
TABLE V: NOMA-enabled CoMP communication systems: current status of rate optimization schemes.

| References | CoMP Type | System Model | Design Objective | Optimization Method | Main Finding(s) |
|------------|-----------|--------------|------------------|---------------------|-----------------|
| [158]      | Coordinated Beamforming (CB) | Two users per cluster model in a multi-cell multi-user MIMO network | Max. sum rate | SDP and SCA technique in each iteration | The proposed CoMP-NOMA scheme outperforms both CoMP-NOMA scheme with fixed power and NOMA without CoMP for medium to high SNR |
| [159]      | Joint Transmission (JT) | Two/multiple users per cluster a two-tier HetNet multi-cell network | Max. sum rate | A sub-optimal distributed power optimization at each CoMP-BS and KKT optimality conditions | The JT-CoMP-NOMA scheme significantly outperforms the JT-CoMP-OMA scheme with more energy requirements |
| [160]      | Generalized joint transmission CoMP (GCoMP) | A large-scale interference-limited HetNet with randomly distributed users | Max. sum rate | Numerical heuristic algorithms | The Coordinated JT-NOMA scheme significantly increases the throughput in dense networks |
| [161]      |            | Multiple users per cluster model | Max. normalized sum rate | KKT optimality conditions | The sum-rate performance of the proposed scheme outperforms GCOMP-OMA scheme |

is to maximize one of the overall sum-rate [117], [123], [134], weighted sum-rate [133], [135], or, the worst user-rate [119], [132]. On the other hand, if only statistical CSIT is available, then the design objective is to maximize the ergodic sum-rate [116], [129] rather than the actual sum-rate. While obtaining full CSIT helps maximize the system throughput, it comes with additional cost and overhead, especially in frequency division duplex (FDD) systems where reciprocity cannot be used. This motivates the need for system design assuming only limited feedback or partial CSIT [162]. In the work by Yang et al. [121], the number of feedback bits for CSIT is optimized and it is demonstrated that the system throughput (i.e., sum rate) can be increased as the number of feedback bits for CSIT is increased.

In another class of MIMO-NOMA systems known as massive MIMO-NOMA systems, the number of antennas at the BS is much greater than the number of users. The different rate optimization schemes from the literature in this class is provided in Table IV. While the favorable propagation conditions in mMIMO systems say that an individual beam can be formed per user when the number of antennas at the BS is infinite, users with highly correlated user channels are hard to separate through spatial division multiple access (SDMA) with a finite number of antennas. However, as with the cluster-based MIMO-NOMA systems, such users are ideal to be grouped in a cluster if there is sufficient difference in their large-scale fading coefficients [142]. This leads to similar US and PA optimization algorithms as the cluster-based MIMO-NOMA systems. As such, sum-rate optimization problems in such a mMIMO-NOMA setting have been studied in single-cell [143], [144] and multi-cell [147] frameworks using this clustering-based approach.

Further, as highlighted in Table IV, a large amount of work has been conducted in the mMIMO-NOMA systems in the mmWave bands. This is because large antenna arrays is seen as a pre-requisite to successful mmWave deployment as described in Section II-B. While the fundamentals of the rate optimization problems in mmWave bands are similar to those in massive-MIMO systems in other bands, the system model needs to consider the low-rank channels and spatial correlation characteristics that are typical for the mmWave communications [73], [74]. While the high spatial correlation of users is typically a constraint for user separation in MU-MIMO systems, MIMO-NOMA systems operating in the mmWave band can use the clustering approach to exploit this correlation to form a cluster and separate the users in the power domain [74], [151]. Another practical limitation of systems operating in the mmWave bands with mMIMO large scale antenna arrays is that scaling the number of transceivers with the number of antennas is often unfeasible. Hence, unlike with regular MIMO-NOMA systems, the system models studied in the literature often use either analog BF with a single RF chain [89] or a hybrid BF design with a reduced number of RF chains [74], [152], [153]. With these additional constraints in the system model, sum-rate optimization schemes in the mmWave bands have similar US and PA design objectives as those with other MIMO-NOMA schemes, e.g., [73].

B. Rate-optimal NOMA Schemes in Coordinated Multi-Point (CoMP) Systems

The promising performance gains of PD-NOMA schemes in terms of the spectral efficiency and fairness in the single-cell scenarios has motivated extending it to multi-cell scenarios. This is especially true for the weaker cell-edge users who would also increase their achievable rates through CoMP schemes leading to CoMP-NOMA systems resulting in enhancement of both spectral efficiency and network throughput. A summary of the up-to-date work on the rate-optimal CoMP-NOMA systems is provided in Table V. In addition to this list, the performance of two hybrid CoMP-NOMA and CoMP-OMA schemes in heterogeneous ultra-dense networks was investigated in [45]. This was conducted using system-level simulations. The results indicated interesting trade-offs in these networks depending on the roles of the macro- and micro-BSs in the coordinated transmissions, and the density of the micro-BSs.

C. Rate-Optimal NOMA Schemes in Cooperative Communication Systems

The merits of the cooperative transmission schemes lie in the ability of extending the coverage area of the network and of improving the users’ SINR, consequently the users’ rate is improved. This happens by providing some users with multiple copies of the same message while utilizing some form of combining techniques such as the maximum ratio combining...
| Reference | Cooperation Type | Relaying Mode | System Model | Design Objective | Optimization Method | Main Finding(s) |
|-----------|------------------|---------------|--------------|------------------|--------------------|-----------------|
| [186]     | HD-DF            | One BS + one relay + K users, single-antenna nodes | Max. sum rate | Max. sum rate | Lagrangian dual method | The proposed scheme achieves higher throughput as compared with buffer-aided relaying without NOMA scheme and conventional relaying with opportunistic NOMA scheme. |
| [187]     | HD-DF            | One BS + one relay + K users, single-antenna nodes | Max. the strongest user-rate | An alternating optimization-based algorithm | The proposed scheme outperforms the conventional OMA-AF relay scheme. |
| [188]     | HD-DF            | One BS + two relays + two users, single-antenna nodes | Max. sum rate | Sub-optimal solution solved via matching algorithms | The proposed scheme outperforms OFDMA scheme in both capacity and fairness. |
| [189]     | HD-DF            | One BS + three relays + K users, single-antenna nodes | Max. Aggregated throughput for all relays | A layered-algorithm and vertical decomposition | The proposed scheme enhances the overall network throughput as compared with the conventional TDMA scheme. |
| [190]     | HD-DF            | A buffer-aided relay-aided NOMA scheme, single-antenna nodes | Max. long term average network utility | Lyapunov optimization approach | The proposed transmission scheme outperforms an equivalent transmission scheme with power strategy and with OMA strategy. |
| [191]     | HD-DF            | One BS + one relay + K users, BS/users: single antenna, relay: multiple antennas | Max. sum rate | Cutting-set iterative method | The proposed robust NOMA scheme outperforms the non-robust and the conventional OMA scheme counterpart. |
| [192]     | HD-DF            | Dual-hop diamond relay NOMA transmission scheme, single-antenna nodes | Max. sum rate | The global sum-rate optimization problem is solved in a local optimization manner | The proposed scheme achieves better performance in terms of sum rate as compared with conventional cooperative protocol. |
| [193]     | HD-DF            | Single-carrier one-way NOMA scheme, single-antenna nodes | Max. sum rate | Decoupled optimization method | The two proposed algorithms outperform OFDMA scheme. |
| [194]     | HD-DF            | A two-hop relay-aided NOMA scheme, single-antenna nodes | Max. Overall Throughput | D.C. programming transformation and SCA technique | The sum-rate performance of the proposed algorithm is superior to its counterpart without simulated annealing algorithm. |
| [195]     | HD-DF, FD-DF, and Hybrid-DF | A coordinated direct and relay transmission NOMA scheme, BS/users: single antenna, relay: two antennas | Maximin user-rate | The original quasi-concave optimization problem is converted into convex feasibility problem | The performance of the proposed schemes outperform both HD relaying and FD relaying schemes. |
| [196]     | HD-DF, FD-DF, and Hybrid-DF | Two-way relaying NOMA scheme, single-antenna nodes | Maximin sum of UL/DL rates | D.C. programming and lagrangian dual method | The performance of the proposed asymptotic optimal algorithm outperforms the primal-domain solution and the block coordinate descent (BDC) method. |
| [197]     | HD-DF, FD-DF, and Hybrid-DF | Multi-path two-way relaying NOMA scheme, BS/relay: multiple antennas, Users: single antenna | Maximin user-rate | D.C. programming transformation and SCA technique | The sum-rate performance of the proposed scheme is superior to its counterpart in OMA scheme. |
| [198]     | HD-DF, FD-DF, and Hybrid-DF | A multi-carrier relay-aided NOMA scheme, single-antenna nodes | Maximin weighted sum-rate | Monotonic optimization and SCA technique | The performance of the proposed scheme outperforms both the random power allocation scheme and the conventional OMA scheme. |
| [199]     | HD-DF and FD-DF  | Two NOMA-based cooperative broadcasting/multicasting schemes for V2X communications, single-antenna nodes | Maximin user-rate | Bisection algorithm | Both proposed schemes achieve better performance than a NOMA scheme with fixed power allocation as well as an optimized TDMA scheme with an increase in the signaling overhead. |
| [200]     | HD-DF and FD-DF  | BS + two users, BS/strong user: multiple antennas, weak user: single antenna | Max. the strong user-rate | Iterative SDP and lagrangian dual method | The proposed schemes have better performance as compared with the direct transmission scheme. |
| [201]     | HD-DF and FD-DF  | A two-stage MISO SWIPT-NOMA cooperative transmission scheme, BS: multiple antennas/single antenna, users: single-antenna | Maximin user-rate | Semi-definite relaxation (SDR) technique and an SCA based algorithm | The sum rate of the proposed scheme in both MISO and SISO cases outperforms its counterparts either without SWIPT or with OMA scheme. |
| [202]     | HD-DF and FD-DF  | BS + two users, single-antenna nodes, (No link between BS and weak user) | Maximin user-rate | Analytical method | The proposed scheme outperforms both the random power allocation scheme and the conventional OMA scheme. |
| [203]     | User-assisted    | Cooperative MIMO-NOMA scheme, multiple-antenna nodes | Maximin user-rate | SCA and SDR techniques | The robust cooperative NOMA scheme is superior to the robust non-cooperative NOMA and TDMA schemes in terms of the strong user data rate. |
| [204]     | User-assisted    | Cooperative Het-nets NOMA scheme, single-antenna nodes | Maximin user-rate | SDP technique, S-procedure, and SCA techniques | The proposed scheme outperforms the counterpart OMA scheme and achieves close performance to optimal exhaustive search algorithm. |
| [205]     | User-assisted    | Cooperative MIMO-NOMA scheme, single-antenna nodes | Maximin user-rate | Sub-optimal convex-concave procedure-based algorithm and a search based sub-optimal algorithm | The proposed cooperative scheme outperforms the conventional NOMA and OMA schemes without cooperation. |
| [206]     | User-assisted    | Cooperative Het-nets NOMA scheme, single-antenna nodes | Maximin user-rate | Three-sided matching algorithm | The proposed scheme outperforms the counterpart OMA scheme and achieves close performance to optimal exhaustive search algorithm with lower complexity. |
| [207]     | User-assisted    | Downlink SWIPT cooperative relaying NOMA scheme, strong user: multiple antennas, BS/weak user: single antenna | Max. the strong user-rate | Alternative optimization (AO) based algorithm | The proposed scheme achieves higher data rate performance for the strong user compared to FD-NOMA without SWIPT, HD-NOMA with SWIPT, and conventional OMA with SWIPT schemes. |
| [208]     | User-assisted    | A SWIPT cooperative NOMA scheme, BS: multiple antennas, users: two antennas | Max. sum rate | D.C. programming transformation | The proposed scheme is superior to the non-cooperative NOMA scheme in terms of the OMA-BF scheme in terms of the sum rate. |
| [209]     | User-assisted    | HYBIRD SWIPT cooperative NOMA scheme with transmit power adaptation, BS single antenna, users: two antennas | Maximin user-rate | Transformation to quasi-concave then conversion into series of convex feasibility problems | The proposed hybrid scheme outperforms HD cooperative NOMA, FD-cooperative NOMA, and the conventional NOMA schemes. |
| [210]     | User-assisted    | A V2I NOMA-NOMA system, BS: single antenna, users: multiple antennas | Maximin user-rate | Bisection algorithm | The maximum capacity performance of SM-NOMA system outperforms the SM-OMA system. |
| [211]     | User-assisted    | A dynamic weight clustering method and a power control strategy based on NOMA scheme, single-antenna nodes | Maximin user-rate | An interval based dichotomy method | The Maximum achievable rate performance of cluster-head in the proposed scheme is superior to that of the conventional NOMA scheme [189] and fixed NOMA scheme [15]. |
TABLE VI(b): Cooperative NOMA communication systems: current status of rate optimization schemes.  

| References | Cooperation Type | Cooperation Mode | System Model | Design Objective | Optimization Method | Main Finding(s) |
|------------|------------------|------------------|--------------|------------------|---------------------|-----------------|
| [190]      | D2D pairs        | One BS + K cellular users + K D2D pairs, single-antenna node | Max. sum rate of all D2D pairs | A dual-based iterative algorithm | The sum-rate performance of the proposed scheme outperforms the OMA-based D2D scheme |
| [191]      | D2D pairs        | One BS + N cellular users + D D2D pairs, cellular users are clustered into groups, single-antenna nodes | Max. sum rate of all D2D pairs | Differential evolution algorithm and SCA technique | The sum rate and energy efficiency performance of the proposed scheme outperforms the OMA-based D2D scheme |
| [192]      | D2D groups (three users per group) | One BS+M cellular users + N D2D pairs, uplink transmission with an D2D underlay mode, single-antenna nodes | Max. sum rate | SCA technique | The proposed scheme achieves higher sum-rate performance and can accommodate larger number of accessed users than the OMA-based D2D scheme |
| [193]      | D2D pairs        | One BS+M cellular users + N D2D pairs, uplink transmission with an D2D interlay and an D2D underlay modes, single-antenna nodes | Max. sum rate | A graph-based algorithm based on BnB method | The interlay mode achieves higher D2D access rate than the conventional underlay mode |
| [194]      | D2D pairs        | One malfunctioning BS + one UAV as BS + multiple UAV users served on an OFDMA basis+ M D2D pairs, single-antenna nodes | Max. sum rate of all D2D pairs | D.C. programming transformation and a low complexity algorithm that exploits the Hessian matrix structure | The D.C. approach provides a high complexity and maybe unpractical solution, and the low complexity approach is more tractable to UAV scenarios and can always converge to a suboptimal solution |
| [195]      | D2D pairs        | One malfunctioning BS + one UAV as BS + Two UAV users served on a NOMA basis + M D2D pairs, single-antenna nodes | Max. sum rate of all D2D pairs | The non-convex problem is relaxed into a standard linear programming form by introducing a series of auxiliary variables | The sum-rate performance of the proposed scheme is slightly less than that of D.C. approach [194] but with a low computational complexity |
| [196]      | A D2D pair       | One BS+K cellular users served on a NOMA basis +one D2D pair, single-antenna nodes | Max. sum rate of all D2D pairs | An analytical framework and a sub-optimal low complexity solution based on gradient algorithm | The proposed scheme is superior to the corresponding OFDMA scheme |
| [197]      | V2V pairs and V2V groups | A V2X-NOMA system that includes V2I, multiV2V, and uniV2V transmission links, single-antenna nodes | Max. sum rate | Hypergraph coloring algorithm | The proposed scheme achieves better/worse sum-rate performance under light/heavy vehicle traffic than that without NOMA scheme as NOMA scheme is more sensitive to inter-group interference |
| [198]      | V2V pairs and V2V groups | Similar to [197], but with more realistic interference environment | Max. sum rate | 3-partite hypergraph | The proposed V2X-NOMA system with greedy/iterative 3-dimensional matching allocation algorithms achieve higher sum-rate performance with low/an acceptable increase in the computational complexity than that of V2X-NOMA/OMA system with random allocation algorithms |

(MRC). Recently, the adoption of the cooperative communication systems in conjunction with NOMA has received a lot of interest [163]–[165], [167], [168], [170]–[172], [174]–[176], [178]–[182], [184]–[188], [190]–[192], [197]–[199]. This is due to the advantage of the spatial diversity gain in improving the users’ rate while enhancing the spectral efficiency of the network [179]. A summary of the up-to-date work on the rate-optimal NOMA schemes in relay-assisted, user-assisted, and device-to-device (D2D) cooperative communication systems is provided in Table VI(a) and Table VI(b).

From the outlined work provided in both Table VI(a) and Table VI(b), one can observe that researchers have investigated cooperative NOMA schemes under three types of cooperation, namely, relay-assisted, user-assisted, and D2D transmission as follows:

(i). Relay-assisted cooperative NOMA schemes:

1) In this variant, a BS sends a superimposed signal to a relay, then the relay forwards the received signal to two or K users through DF or AF modes. Subsequently, the users perform SIC procedures to decode the signal sent from the relay as described in Section II-A. This system model is adopted by several researchers [163]–[165], [167], [168], [170], [171].

2) In this case the system model is similar to the previous one, but there exists an additional communication link between the BS and the strong user. Usually in this setup the objective of the optimization is to maximize the strong user-rate while assuring an acceptable rate to the weak user as proposed in [172].

3) Alternately, a two-way relaying model, where uplink users transmit signals to a relay using uplink NOMA scheme and then the relay broadcasts the superimposed signal to other downlink users. This model is usually deployed in decentralized networks that aim to reduce the signaling overhead and the deployment overhead of the centralized networks as proposed in [174], [175], [199].
1) In this case, a BS transmits a superimposed signal through NOMA scheme to two users that have different channel gains. The strong user uses DF or AF modes to forward the signal to the weak user which employs SIC to decode its own message. Such a model was studied in [178], [180]–[182], [184]–[186].

2) Another system model is similar to the previous one but without a direct link between the BS and the weak user. This model is useful to extend the network coverage and was proposed by Zhang and Jia [179].

(iii). D2D cooperative communication system models [190]–[192]; such system models have been considered to improve the spectral efficiency and to reduce the end-to-end latency.

(iv). V2X cooperative communication system models [176], [187], [188], [197], [198]. These models cover all the previous possibilities which are (i) relay-assisted, (ii) user-assisted, (iii) V2V cooperation types. Such models were proposed to enhance connectivity and to improve spectrum efficiency.

D. Rate-optimal NOMA Schemes in Cognitive Radio Communication Systems

The main aim of cognitive radio communication systems is to improve the utilization of the spectrum. Therefore, PD-NOMA schemes are adopted in conjunction with CR to further enhance the system spectral efficiency. A summary of the up-to-date work on the rate-optimal CR-NOMA schemes is provided in Table VII. One can notice from the outlined work in Table VII, that researchers have investigated three main system models, namely: (i) conventional cognitive radio [76], [200], [204], (ii) cognitive radio in heterogeneous networks (i.e., with macro-BS(s) and femto-BS(s) setting) [109], [201], and (iii) cognitive radio with cooperative communication systems, namely, relay-assisted [203], user-assisted [205], relay-assisted and user-assisted [202].

E. Rate-optimal NOMA Schemes in VLC Systems

Although VLC systems have abundant free bandwidth, the current off-the-shelf LEDs have limited bandwidth which necessitates the adoption of spectrally efficient schemes like NOMA to attain the desired high data rates. Moreover, indoor and low mobility VLC systems have the attractive features of quasi-static nature of the propagation channel and relatively high SNR conditions, especially for short-distance communications and clear LoS conditions, as these features allow more reliable estimation of the channel gains and SIC, respectively. A summary of the up-to-date work on the rate-optimal NOMA-enabled VLC systems is provided in Table VIII for different trans-receive configurations.

It should be highlighted here that unlike RF systems, where the input is typically assumed to be scalar or vector with Gaussian distribution, the capacity-achieving inputs for amplitude-constrained multi-user multiple-access and broadcast VLC and optical channels are still, in general, open problems [213]–[215] and the capacity bounds and/or the modulation schemes such as the pulse-amplitude modulation, on-off keying, and the pulse-position modulation are widely used in optimizing the achievable rates.

F. Rate-optimal NOMA Schemes in UAV Assisted Communication Systems

As described in Section II-G, the use of UAVs in 5G and beyond communication systems is fast growing. The typical use-case studied in UAV-NOMA systems is when the UAV acts as a flying BS and provides a capacity boost to an existing terrestrial network [49]. The goal is to serve more users by scaling up the number of BSs in an ad-hoc fashion to meet any unprecedented traffic needs. PD-NOMA scheme also aims to serve more users concurrently. This is accomplished via non-orthogonal spectrum sharing. For further spectral efficiencies gains, the two technologies can be combined to have the flying BSs to serve users through the NOMA scheme. This UAV-NOMA framework adds an extra degree of freedom to the rate optimization problem by allowing for choice of UAV placement, altitude, and trajectory. In this section, we survey how this additional degree of freedom has been exploited by researchers in such UAV-NOMA systems [216]–[219], [221].

Table IX summarizes the existing literature on rate optimization schemes in UAV-NOMA systems. The system models typically involve a UAV acting as a flying BS and multiple users served by the UAV [217]–[219]. As described in earlier sections, the design variables in the rate optimization problems for NOMA schemes typically involve power allocation, user scheduling, or even beam design if multiple antennas are available. In UAV-NOMA systems, there is the additional design variable of the UAV placement (the location in the 3D space). In the work by Liu et al. [217] the sum rate is maximized through an algorithm that first finds an optimal placement for the UAV, followed by the PA coefficients. In another work by Sun et al. and Nasir et al. [218], [219], a joint optimization of the UAV placement with other design variables is considered for a max-min rate optimization problem. In [218], it is only the UAV placement and PA that is jointly optimized; while in [219], the authors jointly optimize several design variables including the UAV altitude, user scheduling, PA, and the transmit antenna beamwidth. While allowing for flexible UAV placement can help increase the spectral efficiency, the energy efficiency is inversely related to the UAV altitude. Hence, the authors in [216] studied a scheme with fixed UAV altitude and compared it with a scheme where the UAV altitude was allowed to be optimized by the algorithm. The authors showed that there are significant spectral efficiency gains from allowing the UAV altitude to be optimized, but at the cost of energy efficiency.

As the UAV is used as an add-on to a terrestrial network, multiple users will be served partly by a ground BS and partly by the UAV acting as a flying BS. In such a model, the UAV transmissions will cause interference to the BS-served users. The study in [221] addresses such a scenario with a two-part strategy: (i) in the first, a joint user scheduling and UAV
TABLE VII: Cognitive Radio NOMA communication systems: current status of rate optimization schemes.

| References | Cognitive Paradigm | System Model | Design Objective | Optimization Method | Main Finding(s) |
|------------|--------------------|--------------|------------------|--------------------|-----------------|
| [76]       |                   | Half-duplex and full-duplex cognitive OFDM-NOMA systems, single-antenna nodes | Max. weighted sum rate of secondary network | The three decomposed problems are solved based on the bisection algorithm, matching theory, and Lagrangian dual method together with Newtons method. Also, an alternate iteration framework has been proposed for joint optimization | The both HD and FD cognitive OFDM-NOMA systems outperform the traditional cognitive OFDMA system |
| [200]      | Underlay          | Video transmission in NOMA-based cognitive wireless networks, single-antenna nodes | Maxmin rate of secondary users | SCA technique, binary search, and dual decomposition methods | The proposed algorithm improves the minimum video quality and achieves fairness among different secondary users |
| [201]      | Underlay          | NOMA assisted cognitive radio femtocell networks, single-antenna nodes | Max. sum rate of secondary network | SCA technique, KKT optimality conditions, and a greedy algorithm | The proposed scheme enhances the sum rate of the femto-cell users as compared with the conventional cognitive radio OMA based-femtocell technique |
| [202]      |                    | Relay-assisted spectrum sharing scheme with user-assisted cooperation in cognitive radio network, single-antenna nodes | Max. sum rate of secondary receivers | The optimization problem is transformed to a convex problem through reformulation, then the closed-form solution is obtained through relaxation | The proposed scheme has been compared with an equivalent scheme but without user-assisted cooperation. The proposed scheme reduces the required transmit power while achieving same rate performance results |
| [203]      |                    | CK network with full-duplex relay-assisted transmission, relay: multiple antennas, BS: single antenna, and users: single antenna | Max. the rate of near secondary user | SDR in conjunction with line-search approach | The proposed scheme improves both the near and far secondary users rates as compared to the HD mode |
| [204]      | Underlay and overlay | A NOMA based SWIPT scheme, single-antenna nodes | Max. sum rate | Dichotomy method | The proposed scheme can achieve a maximum sum rate via setting an optimal sensing time for the secondary network |
| [205]      | Overlay           | A joint OMA and NOMA transmission protocol in an industrial cooperative-cognitive network, single-antenna nodes | Max. secondary transmitter rate | The two decomposed optimization problems are solved through a linear search algorithm | The performance of the proposed joint OMA and NOMA protocol outperforms OMA schemes |
| [109]      | Interweave        | A two-tier cognitive radio heterogeneous NOMA scheme, single-antenna nodes | Max. the sum rate of second-tier small-cells network | D.C. programming transformation and KKT optimality conditions | The sum rate performance of the proposed small-cell scheme outperforms its counterpart of NOMA scheme with equal power allocation and with OFDMA |

TABLE VIII: VLC-NOMA communication systems: current status of rate optimization schemes.

| References | Classification | System Model | Design Objective | Optimization Method | Main Finding(s) |
|------------|----------------|--------------|------------------|--------------------|-----------------|
| [206]      | Single-cell    | Downlink VLC-NOMA scheme, one LED + K photodiodes | Max. sum rate | KKT optimality conditions | The sum-rate performance of the proposed scheme outperforms the OFDMA scheme with some additional computations |
| [207]      |                | Downlink OFDM-based VLC-NOMA scheme, four LEDs + K photodiodes | Max. sum rate | Analytical method | The proposed power allocation algorithm outperforms the fixed power allocation (FPA) and the gain ratio power allocation (GRPA) algorithms in terms of sum rate |
| [208]      |                | Downlink VLC-NOMA scheme, one LED + two photodiodes | Max. sum rate | SCA technique | The sum rate performance of the proposed optimized VLC-NOMA scheme outperforms the conventional VLC-NOMA scheme for both a LoS and a LoS+NLoS systems |
| [209]      |                | Downlink VLC-NOMA scheme, one LED + K photodiodes | Max. sum rate | Standard interior point method | The proposed scheme achieves higher system sum-rate performance as compared with equivalent schemes of the gain ratio power allocation (GRPA) and of the fixed power allocation (FPA) |
| [210]      |                | A downlink power-line-fed VLC-NOMA scheme, one LED + K photodiodes | Max. sum rate | KKT optimality conditions | The proposed scheme achieves higher system sum-rate performance as compared with equivalent schemes of the normalized gain difference power allocation (NGDPA) and FPA |
| [211]      | Multi-cell     | Ultra-dense VLC hybrid OMA and NOMA scheme, eight LEDs + six photodiodes | Max. sum throughput | A dynamic programming based 1th layer-recursion model | The proposed hybrid NOMA-OMA scheme outperforms the conventional TDMA and NOMA schemes in terms of the achievable throughput |
| [212]      |                | A user grouping-based VLC-NOMA scheme, four LEDs + K photodiodes | Both max. sum rate and maxmin user-rate | Gradient projection (GP) algorithm | The proposed NOMA scheme achieves a higher sum-rate performance than the OMA scheme |
TABLE IX: UAV-NOMA assisted communication systems: current status of rate optimization schemes.

| References | Category | System Model | Design Objective | Optimization Method | Main Finding(s) |
|------------|----------|--------------|------------------|---------------------|-----------------|
| [216]      |          | One UAV + two users, single-antenna UAV, users | Max. sum rate      | Exhaustive search   | The proposed UAV altitude and PA scheme outperforms OMA in a similar system model setting |
| [217]      |          | One UAV + multiple users, single-antenna UAV, users | Max. sum rate      | Break down non-convex problems into convex problems with KKT optimality conditions | The proposed UAV placement and PA scheme outperforms OMA and fixed PA NOMA schemes |
| [218]      | UAV as BS (no ground BS) | One UAV + multiple users, single-antenna UAV, users | Maxmin user-rate   | BCD method          | The proposed joint optimization of UAV placement and user scheduling can double the sum rate compared to cyclical TDMA scheduling |
| [219]      |          | One UAV + multiple users, single-antenna UAV, users | Maxmin user-rate   | Path following algorithm | The proposed joint optimization of multiple design variables improved the sum rate significantly compared to OMA |
| [220]      |          | One UAV + multiple users, single-antenna UAV, users Joint OMA + NOMA transmission modes | Maxmin user-rate   | Penalty dual decomposition method | Proposed method outperformed benchmarks for OMA only or NOMA only based user scheduling. |
| [221]      | UAV as BS (with ground BS) | One BS + one UAV + multiple users, multi-antenna BS, single-antenna UAV and users | Max. sum rate      | Iterative algorithm using BCD method | The proposed low complexity algorithms that steer the UAV close to its users and away from BS served users |
| [222]      |          | One BS + UAV as a user + ground-users, uplink communication with ground BSs that co-operate with each other | Max. WSR of UAV and ground users | Alternating algorithm and SCA technique | The proposed scheme achieved significant sum-rate gains compared to OMA and non-cooperative schemes |

A trajectory iterative optimization scheme is designed for the UAV-served users; and, (ii) in the second, a NOMA precoding scheme is developed for the BS-served users to cancel the interference from the UAV-served users. This is accomplished by exploiting the multiple antennas available at the BS.

In the work by Mei et al. [222], an uplink system model of BSs that co-operate with each other, one UAV and multiple ground users are considered. However, in this case, the UAV is considered as an uplink user rather than a flying BS. Hence, the ground BS has to serve the UAV as well as the ground users. In this model, the higher the UL rate for the UAV, the more the interference to the ground users. As a result, the weighted sum rate of the UAV and ground users is optimized through a user scheduling and power allocation algorithm.

IV. FUTURE RESEARCH DIRECTIONS

The survey documented in this article has revealed performance gains and trade-offs that motivate further investigations of these NOMA-enabled schemes. In the following paragraphs, we highlight some of the possible directions of future research on the integration of PD-NOMA schemes with MIMO/mMIMO, mmWave, CoMP, cooperative communication, cognitive radio, VLC, and UAV communications, and their combinations.

A. MIMO-NOMA, mMIMO-NOMA, and mmWave-NOMA Communication Systems

In Section III-A, we presented the state-of-the-art with respect to rate optimization schemes in MIMO-NOMA systems. Most of the existing work was done in a limited setting of a single cell serving multiple users in a single frequency band. With NOMA being increasingly studied in multi-carrier settings [24], investigating rate optimization schemes with MIMO, NOMA and an OFDM-like multi-carrier technology is a promising research avenue. In such a setting, the user ordering will be different across the different blocks of OFDM sub-carriers, depending on the coherence bandwidth of the channel. This complicates the design of algorithms that rely on a given user ordering like [123]. In general, adding a multi-carrier setting to a MIMO-NOMA system results in a very large number of design variables to the rate optimization problems.

Additionally, a lot of the existing work in MIMO-NOMA systems is focused on the downlink transmission. While the uplink has been a focus of other NOMA schemes, for example the sparse code multiple access (SCMA) [223], only a few works proposed by Ding et al. and Wei et al. [126], [156] consider the uplink in power-domain MIMO-NOMA studies. This is another promising research direction as additional constraints need to be taken into consideration when compared to the downlink transmission. The most important of these is the power budget of the uplink transmitters, especially the low-cost ones typical of the massive machine type connectivity scenarios in 5G [224]. As a result, any power allocation strategy has to consider the end-user capabilities. For example, the cell edge users that have to transmit at higher power in PD-NOMA schemes may not be capable of doing so. Hence, more narrow beams need to be constructed for such users. Clearly, an unexplored research direction is the incorporation of these constraints to a sum-rate optimization problem in an uplink MIMO-NOMA system.

Another potential avenue of research is to use a system model that incorporates 3D-MIMO and NOMA. Vertical beamforming is typically used for tall buildings where beams are formed per floor. The challenge generally with a limited antenna array size is to form beams narrow enough to separate the floors without incurring a large amount of inter-beam interference [85]. The introduction of PD-NOMA to such setting can help alleviate this problem to a great extent, as users within a beam can be separated using NOMA thereby allowing for much wider beams to be formed without affecting the overall sum-rate. This leads to a new set of optimization problems in the vertical dimension in user clustering, beam
design, and power allocation.

Issues pertaining to co-existence of mMIMO and NOMA lead to another area of research not fully explored. In [142], the conditions that favored a hybrid NOMA and mMIMO approach were discussed. However, identifying the right set of users to group for mMIMO versus NOMA is a possible research area worthy of consideration. In particular, algorithms can be designed to switch a user between the traditional MU-MIMO scheme and a MIMO-NOMA clustering scheme depending on the users’ conditions. This user selection problem becomes more important in mmWave-NOMA systems, where mMIMO is a requirement, since analog or hybrid BF is often used to reduce the cost. With analog BF solutions, the BS is only able to produce one beam at a time. Hence, operating with NOMA or a traditional MU-MIMO design can have a significant positive consequence on the sum rate of the system. With 5G systems, exploring communications in a higher frequency range, e.g., above 100GHz [225], even larger antenna arrays are likely be used. Thus, exploring this optimal operating point between MU-MIMO and mMIMO-NOMA becomes significant.

Further, with MIMO-NOMA systems combined with multi-carrier and multi-cell system models, the number of design variables can be prohibitively large to configure in a way that operates at the optimal sum-rate performance. With a data-driven approach being heavily promoted in next-generation communication systems to complement or even replace the traditional model-driven approach [226], there is a large potential for machine learning-based approaches in MIMO-NOMA systems. For example, there is a large amount of data that is collected in every iteration such as the CSI, the performance of a certain user-pairing algorithm, the user data rates, etc. In a traditional approach, this data is simply discarded and the entire model-driven algorithm is re-run for the new system configuration. An unsupervised learning algorithm can try to make sense of this data and identify good user pairs, cluster formations, power allocation strategies or even beam weight designs for more stationary users. It can identify users that can easily be placed in a unique beam vs. users that require a power-domain separation through NOMA schemes. Machine learning can be exploited to identify user characteristics in terms of the rate or SINR characteristics, to help identify whether the beam design should be done for diversity gain or layered transmission. Studies like [227] have identified aspects where machine learning can be exploited in the acquisition of CSIT, which is a key factor in MIMO-NOMA systems. In [83], the authors dedicate an entire section to intelligent mMIMO systems where they highlight the promise of machine learning in mMIMO systems that are hard to capture through a model-driven approach. Adding NOMA on top of that, like with the hybrid approach in [142], makes it harder to model and enhance the argument for a data-driven approach to the problem.

B. CoMP-NOMA Communication Systems

The rate optimization is an attractive topic for future research on CoMP-NOMA systems. This is particularly true as both schemes target enhancing the spectral efficiency of future dense wireless networks. As highlighted in Section II-C, the promising performance gains of joint transmission (please see Table V) are limited in practice by the demanding requirements on the back-haul capacity and the tight synchronization among the coordinated BSs/APs. This fact motivates consideration of the coordinated beamforming version of CoMP-NOMA schemes for future investigation. Further, the performance trade-offs of hybrid CoMP-NOMA and CoMP-OMA schemes need further study, especially in heterogeneous ultra-dense networks. In particular, as is reported [45], [228], CoMP-OMA schemes tend to outperform CoMP-NOMA schemes for high-density micro-BSs networks. Such optimized hybrid schemes are attractive for the evolution of the current 4G and 5G OFDMA-based networks towards 5G networks. Another related interesting direction to investigate is the achievable rates of the recently proposed partial NOMA scheme [229], which allows a partial overlap of the multiplexed users’ signals to reduce the interference among them, with CoMP schemes in heterogeneous networks.

An interesting direction of research for reliability-demanding applications in future networks is to integrate other advanced interference mitigation schemes such as interference alignment schemes. These interestingly would allow a linear scaling of the sum rate with the number of users and can be implemented using linear transceive beamforming schemes [230]–[232], in CoMP-NOMA systems to reduce the inter-cluster interference, as in [233] for a basic multi-cell environment with two users per cell, especially in case of non-orthogonal channel assignment to these NOMA clusters and/or the interference at the non-CoMP users to further enhance the overall network throughput.

C. Cooperative NOMA Communication Systems

The three adopted types of cooperation in cooperative NOMA communication systems in the literature discussed in Section III-C, are envisioned to play a prominent role in future wireless networks. For relay-assisted and user-assisted cooperative NOMA schemes, an area worthy of investigation is the adoption of rate-optimal schemes in V2X systems under low and high mobility scenarios to improve the spectral efficiency as well as to accommodate more vehicles over limited spectrum resources. Furthermore, few number of existing works have studied the rate-optimal cooperative V2X-NOMA systems in downlink setups, for example the study by Chen et al. [187], while rate-optimal cooperative uplink V2X-NOMA systems with single and multi-carrier settings is still an unexplored area. The adoption of V2V cooperative NOMA schemes in V2X systems is highly promising and yet is not well explored.

Other interesting open research problems can be listed as follows: i) The majority of the works in cooperative NOMA systems have investigated either half-duplex or full-duplex communications is a separate fashion. Only two works were found [172], [186] that have studied the potential of dynamic switching between the half-duplex and the full-duplex modes in relay-assisted and user-assisted cooperation types, respectively. Studying the applicability of such a hybrid mode for
D2D cooperative schemes is essential. ii) Several researchers have investigated DF and AF relaying protocols in cooperative NOMA schemes; however, other relaying protocols such as CF and analog network coding (ANC) have been only studied under specific NOMA settings. Particularly, CF relaying protocol with NOMA scheme has been only explored by So and Sung [234] under relay broadcast channel and by Li et al. [205] under an overlay cooperative-cognitive radio network. Studying CF, ANC, and possibly other relaying protocols for different settings and comparing their performance with its counterpart system models that adopt DF and AF relaying protocols are valuable to guide the research community to the optimal relaying protocol for each setting. iii) Cooperative relay sharing NOMA scheme is an interesting topic of research. In this system model, two source-destination user-pairs share a dedicated FD relay between them. This comprises two source-user pairs which utilize UL-NOMA scheme to transmit signals to the relay, then the relay utilizes the superposition coding in DL-NOMA scheme to deliver the signals to its intended destination user-pairs. Such a system can reduce the network deployment cost and also the end-to-end delay. The investigation of the rate-optimal scheme for such setup needs to be conducted. iv) Alsaba et al. [185] have investigated a full-duplex user-assisted cooperative NOMA scheme with perfect and imperfect SI cancellation cases. These cases can be extended to relay-assisted cooperative NOMA systems for different architectures.

D. Cognitive Radio NOMA Communication Systems

As illustrated in Table VII, rate-optimal CR-NOMA schemes outperform the corresponding CR-OMA schemes for single-cell scenarios. More practical system models in multi-cell with single and multiple carriers scenarios under MIMO or mMIMO setups need to be explored to further enhance the network performance and its trade-offs. Furthermore, as stated in Section III-D, rate-optimal CR-NOMA schemes have been adopted only in heterogeneous networks as well as with relay-assisted and user-assisted cooperative communications in order to achieve better spectrum utilization, and to add multiple design dimensions to the previously mentioned networks. In addition to that, more research on the adoption of rate-optimal CR-NOMA schemes in other emerging communication systems such as V2X communications, D2D cooperative communications, internet of things networks, etc., is required. Also, in [205], a hybrid NOMA-OMA transmission protocol in an overlay cooperative-cognitive network has been proposed and applying such a transmission scheme for other CR paradigms and architectures can be an interesting future research direction as such a scheme can offer better system performance than NOMA or OMA schemes separately. Moreover, in [203], two uplink information transmission CR-NOMA schemes under the conditions of two different CR paradigms, namely underlay and overlay, have been proposed. Extending such uplink schemes to different CR architectures can be an interesting topic of research.

E. VLC-NOMA Communication Systems

As evident in Table VIII, only a few works have considered the optimization of the achievable data rates in VLC-NOMA systems and networks. Moreover, most of them have considered the single-cell scenario which motivates future work for the more practical multi-cell scenarios for both VLC and hybrid RF/VLC networks. This is for the different trans-receive arrangements, especially for outdoor applications where channel conditions can change fast and more interference sources are present as compared to those in indoor applications. Also, the use of VLC in V2V and in general V2X communications [235], [236], to replace or complement the existing dedicated short-range communication (DSRC) scheme, has attained high data rates. This would enable future high-definition and real-time applications required for safe, secure, and energy-efficient better informed or autonomous driving that have appeared in 5G networks and are expected to be fully realized in 6G networks. However, weather, road conditions, background solar radiation, and other light sources tend to limit the reliability of long-range V2V VLC which motivates the adoption of NOMA schemes in dense V2V VLC networks [29]. This will also enhance the spectral efficiency and guarantee user fairness. The low SNR at the receiver, and changing channel conditions, require the design of robust VLC-NOMA systems. This will ensure the quality of SIC decoding, along with rate-maximizing user clustering, beam-forming, and power allocation schemes, as well as the LEDs placement and the optical receiver arrangement (receiver type, FOV size and orientation, optical filtering,...) in dense and dynamic vehicular networks. Furthermore, cooperative VLC-NOMA, CR-VLC-NOMA, MIMO-VLC-NOMA, and VLC-NOMA with CoMP systems can be utilized to extend the communication range, enhance the spectral efficiency, and increase the achievable rates in these networks. An example would be the use of multi-hop relaying in platooning applications in NOMA-enabled V2V VLC networks.

F. UAV-NOMA Assisted Communication Systems

As can be seen from Table IX in Section III-F, the combination of UAV and NOMA is a very new field with a large number of unexplored research directions. Most existing rate optimization schemes are in the context of one UAV acting as a flying BS and serving multiple users. In [221], this model was extended to consider the interference caused to users served by a ground BS. However, as described in Section III-F and evidenced by the tutorial in [113], the UAV-NOMA system has multiple ways of using the UAV and sum-rate optimization problems in each of these frameworks are promising directions of future research. As an example, in [222], the use case with the UAV as a flying user is explored. The most interesting of these scenarios arguably is the introduction of NOMA to a multi-tier terrestrial and aerial framework involving ground BSs for long term deployment, LAP flying UAV BSs for flexible short-term deployment, and some HAP UAV BSs for medium-term deployment as described in [113]. Tackling the sum-rate optimization problem with NOMA included in such a complex system model is an area of future research.
Further, the rate optimization schemes from other sections surveyed in this paper can be applied to a UAV-NOMA system with the additional flexibility of the UAV altitude and placement. For example, MIMO-NOMA and mMIMO systems can be enhanced to consider the UAV placement problem in them. The ground BSs, UAVs or the users can all be equipped with multiple antennas, leading to beam design, power allocation, UAV placement, and user scheduling optimization problems. Similarly, co-operative schemes that involve relays can be adapted to have the UAV act as a relay. This gives additional degrees of freedom because the location of the relay can be optimized to be closer to the BS or to the user as required. As a relay link, the UAV could even move between the different hops of the transmission. This leads to interesting power allocation co-efficient design problems. CoMP-NOMA systems with UAV is also an important unexplored area, since the BS and UAV can co-operate to jointly set the design variables involved in a UAV-NOMA system that aims to maximize the sum rate. The UAV-NOMA model can also be applied to other 5G technologies, for example, the authors in [237] have applied the UAV-NOMA model to self-sustaining backscatter networks that do not require external power supply [238].

V. CONCLUSIONS

In this paper, a comprehensive review of the literature was conducted on the integration of PD-NOMA with the main candidate communication technologies and schemes for current and future wireless networks including MIMO/mMIMO, mmWave, COMP, cooperative communication, cognitive radio, VLC, and UAV communications. Particularly, the survey has investigated the system models and the various utilized optimization methods for each NOMA-enabled technology, and revealed the increased achievable rates and the associated trade-offs. Furthermore, a set of possible directions of future research are presented. It should be emphasized here that although the list of the investigated references up to the best of the authors’ knowledge, is quite comprehensive, it is yet not exhaustive and the reader might possibly find some other related references to rate maximization in the combination on PD-NOMA and the enabling technologies and schemes considered in this paper. Moreover, the interested reader may further investigate the literature on multi-objective optimization problems that involve the achievable rates and other performance metrics such as joint optimization of the spectral efficiency and energy efficiency and its trade-offs.

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