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Application of Non-orthogonal Multiple Access in LTE and 5G Networks

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and H. Vincent Poor

Abstract

As the latest member of the multiple access family, non-orthogonal multiple access (NOMA) has been recently proposed for 3GPP Long Term Evolution (LTE) and envisioned to be an essential component of 5th generation (5G) mobile networks. The key feature of NOMA is to serve multiple users at the same time/frequency/code, but with different power levels, which yields a significant spectral efficiency gain over conventional orthogonal MA. This article provides a systematic treatment of this newly emerging technology, from its combination with multiple-input multiple-output (MIMO) technologies, to cooperative NOMA, as well as the interplay between NOMA and cognitive radio. This article also reviews the state of the art in the standardization activities concerning the implementation of NOMA in LTE and 5G networks.

I. INTRODUCTION

Non-orthogonal multiple access (NOMA) has been recently recognized as a promising multiple access (MA) technique to significantly improve the spectral efficiency of mobile communication networks [1-4]. For example, multiuser superposition transmission (MUST), a downlink version of NOMA, has been proposed for 3rd generation partnership project long-term evolution advanced (3GPP-LTE-A) networks [5]. Furthermore, the use of NOMA has also been envisioned as a key component in 5th generation (5G) mobile systems in [6] and [7].

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The key idea of NOMA is to use the power domain for multiple access, whereas the previous generations of mobile networks have been relying on the time/frequency/code domain. Take the conventional orthogonal frequency-division multiple access (OFDMA) used by 3GPP-LTE as an example. A main issue with this orthogonal multiple access (OMA) technique is that its spectral efficiency is low when some bandwidth resources, such as subcarrier channels, are allocated to users with poor channel conditions. On the other hand, the use of NOMA enables each user to have access to all the subcarrier channels, and hence the bandwidth resources allocated to the users with poor channel conditions can still be accessed by the users with strong channel conditions, which significantly improves the spectral efficiency. Furthermore, compared to conventional opportunistic user scheduling which only serves the users with strong channel conditions, NOMA strikes a good balance between system throughput and user fairness. In other words, NOMA can serve users with different channel conditions in a timely manner, which provides the possibility to meet the demanding 5G requirements of ultra-low latency and ultra-high connectivity [6].

In this article, we first provide an introduction to the basics of NOMA, such as typical NOMA power allocation policies, the use of successive interference cancellation (SIC) and the relationship between NOMA and conventional information theoretic concepts, where a simple example with two users is used to illustrate the benefit of NOMA. This introduction is then followed by a detailed overview of the recent developments in NOMA. We begin by considering the combination of NOMA and multiple-input multiple-output (MIMO) technologies. Various MIMO-NOMA designs will be introduced to achieve different tradeoffs between reception reliability and data rates, since spatial degrees of freedom can be used to improve either the receive signal-to-noise ratio (SNR) or the system throughput. The concept of cooperative NOMA will then be described, where employing user cooperation in NOMA is a natural choice since some users in NOMA systems know the information sent to the others and hence can be used as relays. In addition, cooperative NOMA has the potential to exploit the heterogeneous nature of future mobile networks, in which some users might have better capabilities, e.g., more antennas, than the others. Therefore, the reception reliability of users with poor capabilities can be improved by requesting the ones with strong capabilities to act as relays. The interplay between NOMA and cognitive radio (CR) technologies, which have also been viewed as a key component of next-generation mobile networks, will further be discussed, and standardization activities to implement NOMA in LTE and 5G networks will be also reviewed. Finally research challenges and some promising future directions for designing spectrally and energy efficient NOMA systems will be provided, followed by concluding remarks.

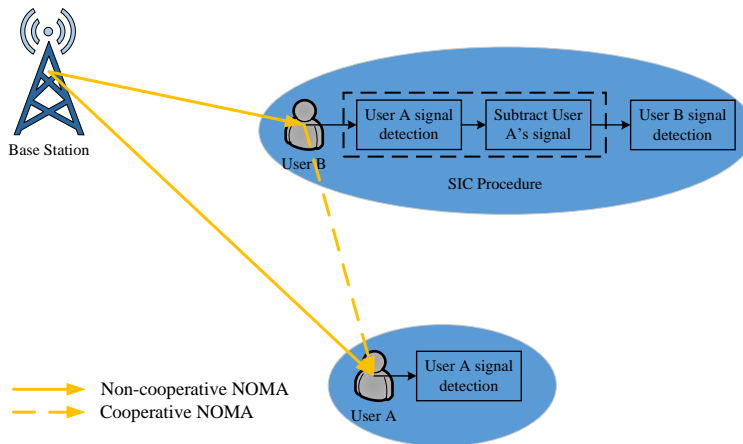


Fig. 1: Illustration of a two-user NOMA network which involves non-cooperative NOMA transmission without considering the cooperative phase illustrated by the dashed line.

II. NOMA BASICS

In order to better illustrate the concept of NOMA, we take NOMA downlink transmission with two users as an example. As shown in Fig. 1, the two users can be served by the base station (BS) at the same time/code/frequency, but with different power levels. Specifically the BS will send a superimposed mixture containing two messages for the two users, respectively. Recall that conventional power allocation strategies, such as water filling strategies, allocate more power to users with strong channel conditions. Unlike these conventional schemes, in NOMA, users with poor channel conditions get more transmission power. In particular, the message to the user with the weaker channel condition is allocated more transmission power, which ensures that this user can detect its message directly by treating the other user's information as noise. On the other hand, the user with the stronger channel condition needs to first detect the message for its partner, then subtract this message from its observation and finally decode its own information. This procedure is called SIC (as shown in Fig. 1).

The performance gain of NOMA over conventional OMA can be easily illustrated by carrying out high SNR analysis. With OMA, the achievable data rates for the two users are $\frac{1}{2} \log_2 (1 + \rho |h_A|^2)$ and $\frac{1}{2} \log_2 (1 + \rho |h_B|^2)$, respectively, where $\frac{1}{2}$ is due to the fact that the bandwidth resources are split between two users, ρ denotes the transmit SNR, h_A and h_B denote the channel gains for User A and User B, respectively. Following Fig. 1, we assume $|h_A|^2 < |h_B|^2$. At high SNR, i.e., $\rho \rightarrow \infty$, the sum rate of OMA can be approximated as $\frac{1}{2} \log_2 (\rho |h_A|^2) + \frac{1}{2} \log_2 (\rho |h_B|^2)$. By using NOMA, the achievable

rates are $\log_2 \left(1 + \frac{\rho a_A |h_A|^2}{1 + \rho a_B |h_B|^2} \right)$ and $\log_2 (1 + \rho a_B |h_B|^2)$, respectively, where a_A and a_B are the power allocation coefficients. Therefore the high SNR approximation for the NOMA sum rate is $\log_2 (\rho |h_B|^2)$, which is much larger than that of OMA, particularly if the channel gain of User B is much larger than that of User A. In other words, the reason for the performance gain of NOMA is that the effect of the factor $\frac{1}{2}$ outside of the logarithm of the OMA rates, which is due to splitting bandwidth resources among the users, is more damaging than that of the factors inside of the logarithm of the NOMA rates, which are for power allocation. It is worth pointing out that NOMA suffers some performance loss at low SNR, compared to OMA.

Downlink and uplink NOMA can be viewed as special cases of multiple access channels (MACs) and broadcast channels (BCs), and therefore the rate regions achieved by NOMA are bounded by the capacity regions of the corresponding MACs and BCs. Compared to existing information theoretic works which mainly focus on the maximization of system throughput, a key feature of NOMA is to realize a balanced tradeoff between system throughput and user fairness. Again take the two-user downlink case as an example. If the system throughput is the only objective, all the power will be allocated to the user with strong channel conditions, which results in the largest throughput, but User A is not served at all. The feature of NOMA is to yield a throughput larger than OMA, and also ensures that users are served fairly. This feature is particularly important to 5G, since 5G is envisioned to support the functionality of Internet of Things (IoT) to connect trillions of devices. With OMA, connecting thousands of IoT devices, such as vehicles in vehicular ad hoc networks for intelligent transportation, requires thousands of bandwidth channels; however, NOMA can serve these devices in a single channel use. An important phenomenon in NOMA networks is that some users with poor channel conditions will experience low data rates. The reason for this is that these users cannot remove their partners' messages completely from their observations, which means that they will experience strong co-channel interference and therefore their data rates will be quite small. In the context of IoT, this problem is not an issue, since many IoT devices need to be served with only small data rates.

III. MIMO NOMA TRANSMISSION

The basic idea of NOMA can be extended to the case in which a BS and users are equipped with multiple antennas, which results in MIMO NOMA. Of course, for downlink transmissions, the BS could use its multiple antennas either for beamforming to improve the signal-to-interference-plus-noise ratio (SINR) [10] or for spatial multiplexing to increase the throughput [11]. We discuss these two options in the following sections.

A. NOMA with Beamforming

NOMA with beamforming (NOMA-BF) can exploit the power domain as well as the spatial domain to **increase the spectral efficiency by improving the SINR**. To see this, we consider a system of four users as shown in Fig. 2. There are two clusters of users. User 1 and User 3 belong to cluster 1, while User 2 and User 4 belong to cluster 2. In each cluster, the users' spatial channels should be highly correlated so that one beam can be used to transmit signals to the users in the cluster. For example, we can assume that $\mathbf{h}_3 = c\mathbf{h}_1$ for cluster 1, where \mathbf{h}_k is the channel vector from the antenna array at the BS to user k , and for cluster 2, we have $\mathbf{h}_2 = c'\mathbf{h}_4$, where c and c' are constants. Furthermore, we assume that the beam to cluster 1 is orthogonal to the channel vectors of the users in cluster 2, and vice versa. That is, $\mathbf{w}_1 \perp \mathbf{h}_2, \mathbf{h}_4$ and $\mathbf{w}_2 \perp \mathbf{h}_1, \mathbf{h}_3$, where \mathbf{w}_m denotes the beam to cluster m .

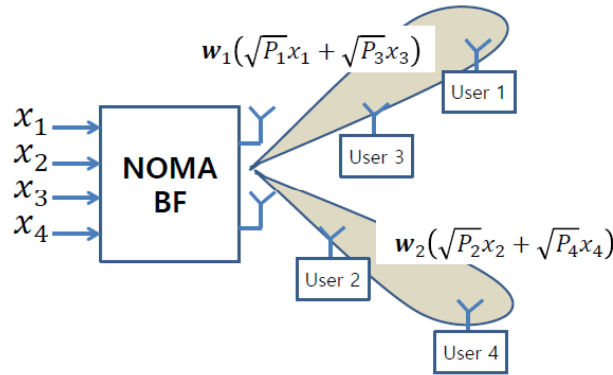


Fig. 2: An illustration of NOMA with beamforming.

Due to beamforming, the signals from one cluster to the other are suppressed. Thus, at a user in cluster 1, the received signal would be a superposition of x_1 and x_3 , while a user in cluster 2 receives a superposition of x_2 and x_4 , where x_k is the signal to user k . As shown in Fig. 2, if User 3 is closer to the BS than User 1, User 3 would first decode x_1 and subtract it to decode x_3 using SIC. User 1 decodes x_1 with the interference, x_3 . Clearly, conventional NOMA of two users can be applied in each cluster. In [8], this approach is studied to support $2N$ users in the same frequency and time slot with N beams that are obtained by zero-forcing (ZF) beamforming to suppress the inter-cluster interference.

A two-stage beamforming approach is proposed using the notion of multicast beamforming in [9]. In [10], it is assumed that the users have multiple receive antennas. Thus, receive beamforming can be exploited at the users to suppress the inter-cluster interference. In this case, the BS can employ a less restrictive beamforming approach than ZF beamforming.

B. NOMA with Spatial Multiplexing

Unlike NOMA-BF, the purpose of NOMA with spatial multiplexing (NOMA-SM) is to increase the spatial multiplexing gain using multiple antennas. In NOMA-SM, each transmit antenna sends an independent data stream. Thus, the achievable rate can be increased by a factor of the number of transmit antennas. This requires multiple antennas at the user as well. This requires multiple antennas at the users. In [11], the achievable rate is studied for NOMA-SM. In principle, NOMA-SM can be seen as a combination of MIMO and NOMA. Recall that the achievable rate of MIMO channels grows linearly with the minimum of the numbers of transmit and receive antennas under rich scattering environments, and therefore, this scaling property of MIMO should also be valid in NOMA with spatial multiplexing. Fig. 3 shows the achievable rate results of NOMA-SM and OMA with different number of antennas (denoted by M) under a rich scattering environment. It is assumed that the number of antennas at the BS is the same as that at a user. The power of the channel gain of the weak user is four-times less than that of the strong user. The total powers allocated to the strong and weak users are 3 and 6 dB, respectively. For OMA, we consider time division multiple access (TDMA) with equal time slot allocation. Thus, each user's achievable rate in OMA is the same as that of conventional MIMO. However, since a given time slot is equally divided between two users, each user's achievable rate is halved. On the other hand, in NOMA, each user can use a whole time slot and have a higher achievable rate that could be two-times higher than that in OMA as shown in Fig. 3.

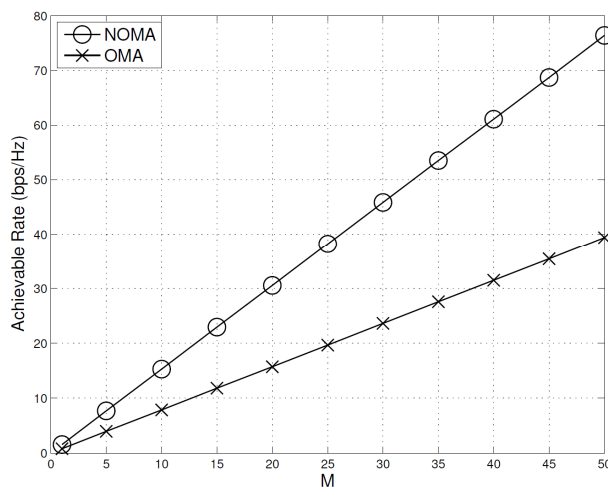


Fig. 3: Scaling property of NOMA with spatial multiplexing.

IV. COOPERATIVE NOMA TRANSMISSION

The basic idea of cooperative NOMA transmission is that users with stronger channel conditions act as relays to help users with weaker channel conditions. Again, take the two-user downlink case illustrated in Fig. 1 as an example. A typical cooperative NOMA transmission scheme can be divided into two phases, namely, direct transmission phase and cooperative transmission phase, respectively. During the direct transmission phase, the BS broadcasts a combination of messages for User A (weaker channel condition) and User B (stronger channel condition). During the cooperative transmission phase, after carrying out SIC at User B for decoding User A's message, User B acts as a relay to forward the decoded information to User A. Therefore, two copies of the messages are received at User A through different channels. A more sophisticated and general cooperative NOMA scheme involving K users was introduced in [12]. The advantages of cooperative NOMA transmission is that, since SIC is employed at receivers in NOMA systems, the messages to the users with weaker channel conditions have already been decoded by the users with stronger channel conditions. Hence it is natural to recruit the users with stronger channel conditions as relays. As a consequence, the reception reliability of the users with weaker channel conditions is significantly improved. The performance improvement of cooperative NOMA is illustrated in Fig. 4. Particularly, Fig. 4(a) and Fig. 4(b) demonstrate that the cooperative NOMA outperforms non-cooperative NOMA in terms of the outage probability of the user pair and the outage probability of the poor user, respectively. In addition, in [12], it is demonstrated that cooperative NOMA achieves a larger outage probability slope than non-cooperative NOMA, which is due to the fact that the former can achieve the maximum diversity gain for all users.

It is worth pointing out that complexity is an important consideration when implementing cooperative NOMA. For example, it is not realistic to combine all users to perform cooperative NOMA. The main challenges are: 1) coordinating multi-user networks will consume a tremendous amount of system overhead, and 2) user cooperation will consume extra time slots. To overcome these issues, a hybrid MA system incorporating user pairing/grouping has been proposed and viewed as a promising solution to reduce the system complexity of cooperative NOMA. Particularly, users in one cell can be first divided into multiple pairs/groups, then cooperative NOMA is implemented within each pair/group while OMA is implemented among pairs/groups. The performance of user pairing was investigated in [14], which demonstrates that pairing users with distinctive channel conditions yields a significant sum rate gain.

Furthermore, it is important to point out that power allocation coefficients have been recognized to have a great impact on the performance of non-cooperative NOMA [1], and thus, investigating optimal

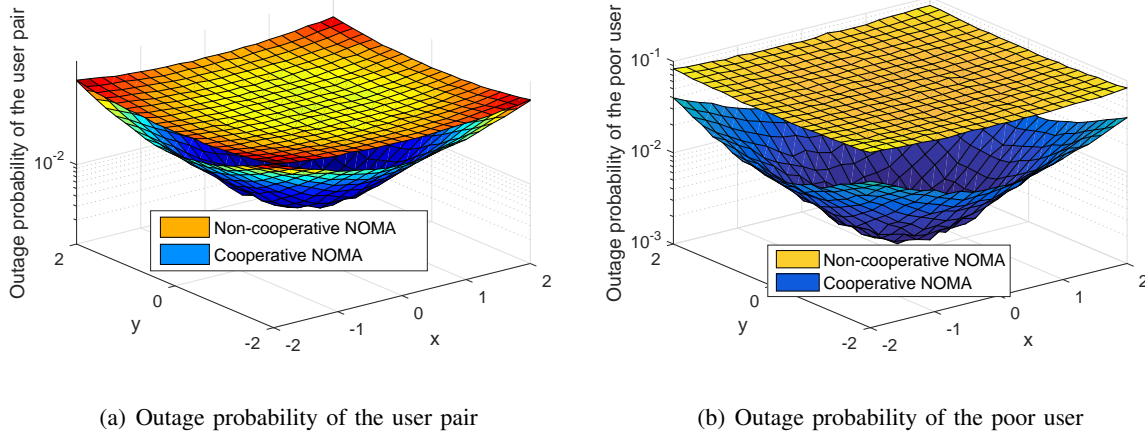


Fig. 4: Performance of Cooperative NOMA transmission – an example. The BS is located at $(0, 0)$. User A is located at $(5m, 0)$. The x - y plane denotes the location of User B. A bounded path loss model is used to ensure all distances are greater than one. The path loss exponent is 3. The transmit signal-to-noise ratio (SNR) is 30 dB. The power allocation coefficient for User A and User B are $(a_A, a_B) = (\frac{4}{5}, \frac{1}{5})$. The targeted data rate is 0.5 bits per channel use (BPCU).

power allocation to further improve the performance of cooperative NOMA systems is an important research topic. There are other promising research directions based on cooperative NOMA. For example, considering simultaneous wireless information and power transfer (SWIPT), the NOMA user with the stronger channel condition can be used as an energy harvesting relay to help the user with the weaker channel condition without draining the latter's battery. A class of cooperative SWIPT NOMA protocols is proposed in [13] and its performance is evaluated by applying stochastic geometry.

V. INTERPLAY BETWEEN COGNITIVE RADIO AND NOMA

NOMA can be viewed as a special case of CR networks. For example, consider a two-user scenario shown in Fig. 1. User A can be viewed as a primary user in a CR network. If OMA is used, the orthogonal bandwidth allocated to User A cannot be accessed by other users, despite the fact that User A has a poor connection to the BS, i.e., the bandwidth resource allocated to this user cannot be used efficiently. The use of NOMA is equivalent to the application of the CR concept. Specifically User B, a user with stronger channel condition, is introduced to the channel occupied by User A. Although User B causes extra interference at User A and hence reduces User A's rate, the overall system throughput will be increased significantly since User B has a strong connection to the BS, as can be observed from Fig. 5(a).

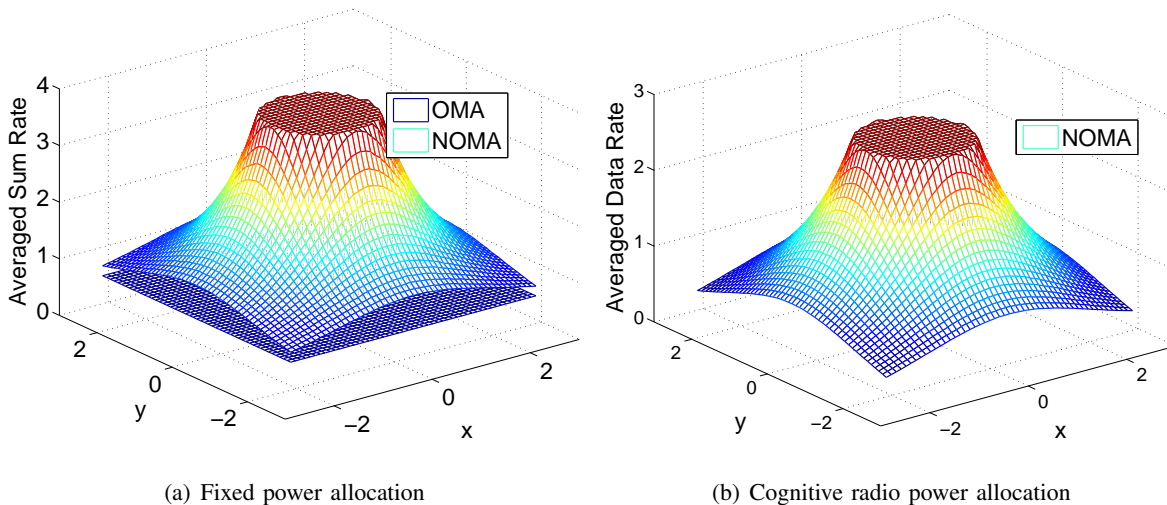


Fig. 5: Performance of downlink NOMA transmission – an example. The transmit SNR is 20 dB. A fixed power allocation policy, $(a_A, a_B) = (\frac{7}{8}, \frac{1}{8})$, is used in the first subfigure. The power allocation coefficient used in the second figure needs to satisfy a targeted data rate of 0.5 BPCU at the primary user. The other parameters are set the same as in Fig. 4.

The analogy with cognitive radio not only yields insight into the performance gain of NOMA, but also provides guidance for the design of a practical NOMA system [14]. For example, NOMA seeks to strike a balanced tradeoff between system throughput and user fairness. However, user fairness can be measured by many different metrics. By using the CR concept, an explicit power allocation policy can be obtained to meet the users' predefined quality of service (QoS). **An example of such CR inspired NOMA networks is illustrated in the following by considering the two-user case shown Fig. 1.** Consider that User A, i.e., the user with weaker channel condition, has a targeted data rate R_1 . Here, **the CR inspired power allocation coefficient a_A needs to satisfy $\log_2 \left(1 + \frac{a_A^2 |h_A|^2 \rho}{(1-a_A^2 |h_A|^2) \rho + 1} \right) \geq R_1$.** **The aim of this CR inspired power allocation policy is to ensure that the QoS requirements at the primary user, i.e., User A, are strictly met,** and the BS can explore the degrees of freedom in the power domain to serve User B opportunistically, as shown in Fig. 5(b). It is worth pointing out that this CR inspired NOMA is particularly useful in the MIMO scenario, where it is difficult to order users according to their channel conditions and hence challenging to find an appropriate power allocation policy [8].

The interplay between cognitive radio and NOMA is bidirectional, where NOMA can also be applied in CR networks to significantly increase the chance of secondary users to be connected. For example, without using NOMA, separated bandwidth resources are required to serve different secondary users, which can

potentially introduce a long delay for secondary users to be served. The use of NOMA can ensure that multiple secondary users are served simultaneously, which effectively increases the connectivity of the secondary users. Power allocation at the secondary transmitters is critical to the application of NOMA in CR networks. Specifically, it is important to ensure that the secondary users are served without causing too much performance degradation at the primary receiver, where the total interference observed at the primary receiver is an important criterion. Furthermore, the power control policy used also needs to ensure that interference among the secondary users is carefully controlled in order to meet the secondary users' QoS requirements.

VI. STATE OF THE ART FOR NOMA IN 3GPP LTE AND 5G

There have been a number of standardization activities related to the implementation of NOMA in next-generation mobile networks. In particular, the standardization organization 3GPP initiated a study item on Downlink MUST for LTE in Release 13, focusing on multiuser non-orthogonal transmission schemes, advanced receiver designs and related signaling schemes [5]. Various non-orthogonal transmission schemes have been proposed and studied in the MUST study item. Based on their characteristics, they can be generally divided into three categories [15], and examples of transmitter processing for these three categories are shown in Fig. 6.

- 1) Category 1: Superposition transmission with an adaptive power ratio on each component constellation and non-Gray-mapped composite constellation.
- 2) Category 2: Superposition transmission with an adaptive power ratio on component constellations and Gray-mapped composite constellation.
- 3) Category 3: Superposition transmission with a label-bit assignment on composite constellation and Gray-mapped composite constellation.

To characterize the gains of the non-orthogonal transmission schemes studied in MUST quantitatively, the initial link level and system level evaluation has been provided by various companies. It is envisioned that almost 20% cell-average and cell-edge throughput gains can be obtained [15]. Other topics supporting the non-orthogonal transmission, e.g., channel state information (CSI) reporting schemes, retransmission schemes, HARQ process design and the signaling schemes associated with the advanced receiver, are still under active discussion.

In addition to MUST, there are other forms of non-orthogonal multiple access schemes, e.g., sparse code multiple access (SCMA), pattern division multiple access (PDMA), multiuser shared multiple access (MUSA), which have also been actively studied as promising MA technologies for 5G [6], [7]:

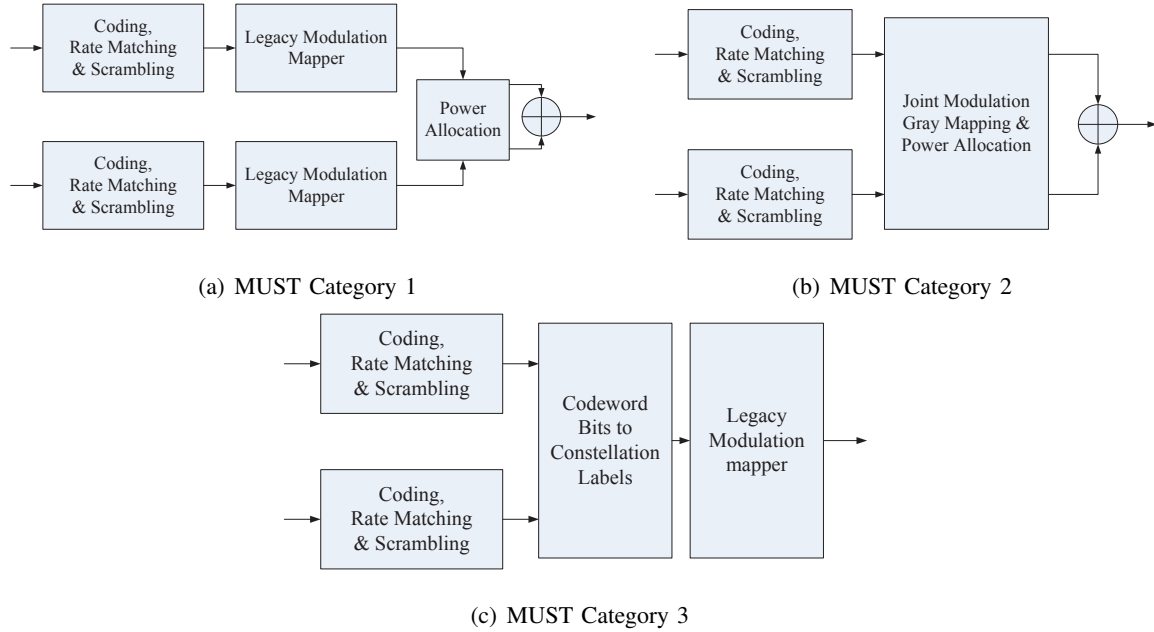


Fig. 6: Examples of transmitter processing of candidate MUST schemes

- 1) SCMA is proposed as a multi-dimensional constellation codebook design based on the non-orthogonal spreading technique, which can be overloaded to enable massive connectivity and support grant-free access. SCMA directly maps the bit streams to different sparse codewords, and different codewords for all users are multiplexed over shared orthogonal resources, e.g., OFDM subcarriers. At the receiver, a low-complexity message passing algorithm is utilized to detect the users' data.
- 2) The uplink MUSA scheme is based on the enhanced multi-carrier code division multiple access (MC-CDMA) scheme. Equipped with advanced low correlation spreading sequences (e.g., I/Q data randomly taking $\{-1, 0, 1\}$ values at the transmitter), linear processing and SIC techniques at the receiver, MUSA can achieve remarkable gains in system performance, especially when the user overloading factor is high, for example, larger than 300%.
- 3) PDMA employs multiple-domain non-orthogonal patterns, which are realized by maximizing the diversity and minimizing the overlaps among multiple users. The multiplexing can be realized in the code, power, and spatial domains or their combinations, which enables high flexibility for coding and decoding processing. PDMA can promote 1-2 times increase of the system spectral efficiency, decrease data transmission delay and enhance quality of experience (QoE) of user access.

It is worth pointing out that these aforementioned MA candidates are closely related to the fundamental principle of NOMA which is to serve multiple users at the same channel use. Take SCMA as an example. The term of sparsity refers to the fact that each user can occupy only a small number of orthogonal channel uses, such as subcarriers, but there is always more than one user occupying each of the subcarriers. Therefore, at each subcarrier, SCMA can be viewed as NOMA, since multiple users are sharing the same bandwidth resource. Or in other words, SCMA can be built by combining NOMA with advanced strategies for subcarrier allocation, coding and modulation.

VII. RESEARCH CHALLENGES

1) *User Pairing/Clustering*: While many examples provided in this article consider two-user downlink scenarios, it is important to point out that NOMA can be applied to general uplink and downlink scenarios with more than two users. However, the use of superposition coding and SIC can cause extra system complexity, which motivates the use of user pairing/clustering, an effective approach to reduce the system complexity since fewer users are coordinated for the implementation of NOMA. However, in cluster-based NOMA systems, it is very challenging to determine how best to dynamically allocate users to a fixed/dynamic number of clusters with different sizes. It is important to point out that the resulting combinatorial optimization problem is in general NP-hard and performing an exhaustive search for an optimal solution is computationally prohibitive. Therefore, it is important to propose new low-complexity algorithms to realize optimal user clustering. Note that the performance of the cluster-based NOMA system can be further improved by opportunistically performing power allocation among different users in each cluster.

2) *Hybrid Multiple Access*: It has been envisioned that future cellular networks will be designed by using more than one MA techniques, and this trend has also been evidenced by the recent application of NOMA to 3GPP-LTE (MUST). Particularly, MUST is a hybrid MA scheme between OFDMA and NOMA, where NOMA is to be used when users have very different CSI, e.g., one user close to the BS and the other at the cell edge. Therefore it is important to study how to combine NOMA with other types of MA schemes, including not only the conventional OMA schemes but also those newly developed 5G MA techniques. Advanced game theoretic approaches can be applied to optimize the use of bandwidth resources in the power, frequency, time and code domains.

3) *MIMO-NOMA*: In NOMA with beamforming, there are still various issues and challenges. For example, optimal joint user allocation and beamforming schemes have not been considered as their computational complexity would be prohibitively high. Joint transmit and receive beamforming is also an

important topic that has not been well investigated yet. The main difficulty for NOMA with spatial multiplexing is the complexity of the receivers of the users. A strong user needs to jointly detect multiple signals twice, which might be computationally demanding. The extension of NOMA with spatial multiplexing to more than two users with multiple carriers also requires user clustering and resource allocation in a multi-dimensional space (i.e., frequency, time, spatial, and power domains), which is an analytical and computational challenge.

4) *Imperfect CSI*: Most existing work on NOMA has relied on the perfect CSI assumption which is difficult to realize, since sending more pilot signals to improve the accuracy of channel estimation reduces the spectral efficiency. Therefore, it is important to study the impact of imperfect CSI on the reception reliability in NOMA systems. Another example of the strong CSI assumptions is that many NOMA protocols require the CSI at the transmitter, which can cause significant system overhead. [The use of only a few bits of feedback is a promising solution in NOMA systems, since obtaining the ordering of users' channel conditions is sufficient for the implementation of NOMA in many applications.](#)

5) *Cross-layer Optimization*: Cross-layer optimization is important to maximize the performance of NOMA in practice and meet the diversified demands of 5G, e.g, spectral efficiency, energy efficiency, massive connectivity, and low latency. For example, practical designs of coding and modulation are important to realize the performance gain of NOMA at the physical layer, and it is crucial to study how to feed these gains from the physical layer to the design of upper layer protocols. This cross-layer optimization is particularly important to NOMA which, unlike conventional MA schemes, takes the user fairness into consideration, which means that the issues related to user scheduling and pairing, power allocation, pilot and retransmission schemes design need to be jointly optimized.

VIII. CONCLUSIONS

In this article, the concept of NOMA has been first illustrated by using a simple scenario with two single-antenna users. Then various forms of MIMO-NOMA transmission protocols, the design of cooperative NOMA, and the interplay between two 5G technologies, NOMA and cognitive radio, were discussed. The recent industrial efforts for the standardization of NOMA in LTE and 5G networks have been conclusively identified, followed by a detailed discussion of research challenges and potential solutions.

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