Abstract—Although non-orthogonal multiple access (NOMA) is recently considered for cellular systems, its key ideas such as successive interference cancellation (SIC) and superposition coding have been well studied in information theory. In this paper, we overview principles of NOMA based on information theory and present some recent results. Under a single-cell environment, we mainly focus on fundamental issues, e.g., power allocation and beamforming for downlink NOMA and coordinated and uncoordinated transmissions for uplink NOMA.

Index Terms—nonorthogonal multiple access; power allocation; beamforming; random access

I. INTRODUCTION

Recently, nonorthogonal multiple access (NOMA) has been extensively studied in [1] [2] [3] [4] for 5th generation (5G) systems as NOMA can improve the spectral efficiency. In order to implement NOMA within standards, multiuser superposition transmission (MUST) schemes are proposed in [5]. There are also review articles for NOMA, e.g., [6] [7].

Although the application of NOMA to cellular systems is relatively new, NOMA is based on well-known schemes such as superposition coding and successive interference cancellation (SIC) [8] [9]. In particular, the decoding approach based on multiple single-user decoding with SIC for multiple access channels has been studied from the information-theoretic point of view under other names such as stripping and onion peeling [10]. In addition, there are precursors of NOMA. For example, code division multiple access (CDMA) is a NOMA scheme as spreading codes are not orthogonal [11] [12] [13]. In order to mitigate the multiple access interference (MAI) due to non-orthogonal spreading codes, multiuser detection (MUD) is also studied [14] [15]. In CDMA, although the notion of superposition coding is not actively exploited, SIC is extensively studied since [16].

The main difference of the NOMA schemes for 5G from existing CDMA schemes is the exploitation of the power difference of users and the asymmetric application of SIC in the power and rate allocation. In particular, these features are well shown in downlink NOMA. In [1] [2], a user close to a base station (BS) and a user far away from the BS form a group or cluster. For convenience, the former and latter users are called strong and weak users, respectively (in terms of their channel gains). It is expected to transmit a higher power to the weak user than the strong user due to the path loss or channel gain. If they share the same radio resource block, the signal to the weak user received at the strong user has a higher signal-to-noise ratio (SNR) than that at the weak user, which implies that the strong user is able to decode the signal to the weak user and remove it (using SIC) to decode the desired signal without MA without MAI. On the other hand, at the weak user, the signal to the strong user is negligible as its transmission power is lower than that to the weak user. Thus, the weak user decodes the desired signal without using SIC.

To exploit the power difference, the power allocation becomes crucial. A power allocation problem for NOMA with fairness is studied in [17] [18]. An energy efficient power allocation approach is investigated in [19]. The power difference between users can also be exploited in a multi-cell system. In [20], NOMA is studied for downlink coordinated two-point systems. In [21], coordinated beamforming is considered for multi-cell NOMA.

In [22] [23] [24], multiple input multiple output (MIMO) for NOMA is studied to see how NOMA can be applied to MIMO systems. Beamforming in NOMA is also studied in [2] [25] [26]. In general, beamforming in NOMA is to exploit the power and spatial domains. In [23], beamforming with limited feedback of channel state information (CSI) is studied. Multicast NOMA beamforming is considered in [27].

Since there have been various NOMA schemes and related approaches, it might be important to have an overview. As mentioned earlier, there are already excellent review articles [6] [7]. However, they focus on system aspects. Thus, in this paper, we aim at providing an overview of key approaches and recent results with emphasis on fundamentals of NOMA under a single-cell environment.

The rest of the paper is organized as follows. In Section II, we present system models for uplink and downlink NOMA. The power allocation problem and downlink beamforming are considered for downlink NOMA in Section III and Section IV, respectively. We focus on some key issues in uplink NOMA in Section II-B and conclude the paper with some remarks in Section VI.

Notation: Matrices and vectors are denoted by upper- and lower-case boldface letters, respectively. The superscripts *, T, and H denote the complex conjugate, transpose, Hermitian transpose, respectively. \( \mathbb{E}[\cdot] \) and \( \text{Var}(\cdot) \) denote the statistical expectation and variance, respectively. \( \mathcal{CN}(\mathbf{a}, \mathbf{R}) \) represents the distribution of circularly symmetric complex Gaussian (CSCG) random vectors with mean vector \( \mathbf{a} \) and covariance matrix \( \mathbf{R} \).
II. SYSTEM MODELS

A. Downlink NOMA

In this section, we present a system model consisting of a BS and multiple users for downlink NOMA. Throughout the paper, we assume that the BS and users are equipped with single antennas.

Suppose that there are $K$ users in the same resource block for downlink. Let $s_{k,t}$ and $h_k$ denote the data symbol at time $t$ and channel coefficient from the BS to user $k$, respectively. The block of data symbols, $[s_{k,0}, ..., s_{k,T-1}]^T$, where $T$ is the length of data block, is assumed to be a codeword of a capacity-achieving code. Furthermore, $T$ is shorter than the coherence time so that $h_k$ remains unchanged for the duration of a block transmission. Suppose that superposition coding [9] is employed for NOMA and the signal to be transmitted by the BS is $\sum_{k=1}^{K} s_{k,t}$. Then, at user $k$, the received signal is given by

$$y_{k,t} = h_k \sum_{m=1}^{K} s_{m,t} + n_{k,t}, t = 0, \ldots, T - 1,$$  \hspace{1cm} (1)

where $n_{k,t} \sim \mathcal{CN}(0,1)$ is the independent background noise (here, the variance of $n_{k,t}$ is normalized for convenience). Let $\alpha_k = |h_k|^2$ and $P_k = \mathbb{E}[|s_{k,t}|^2]$ (with $\mathbb{E}[s_{k,t}] = 0$). Then, $P_k$ becomes the transmission power allocated to $s_{k,t}$. In this section, we assume that the BS knows all the channel gains, $\{\alpha_k\}$, and studies the power allocation to enable SIC at users for NOMA.

B. Uplink NOMA

We again assume that there are $K$ users who are allocated to the same resource block for uplink transmissions. Then, at the BS, the received signal becomes

$$r_l = \sum_{k=1}^{K} g_k u_{k,t} + n_l, \ t = 0, \ldots, T - 1,$$  \hspace{1cm} (2)

where $g_k$ and $u_{k,t}$ represent the channel coefficient from the $k$th user to the BS and the signal from the $k$th user, respectively, and $n_l \sim \mathcal{CN}(0,1)$ is the background noise at the BS. The BS is able to decode all $K$ signals if the transmission rates and powers of the $u_{k,t}$’s are properly decided using single-user decoding. A well-known example of uplink NOMA is CDMA where each user’s signal is spread signal with a unique spreading code [12].

III. POWER ALLOCATION FOR DOWNLINK NOMA

In this section, we briefly study the power allocation for downlink NOMA with achievable rates.

Let $R_{lk}$ denote the transmission rate of $s_{k,t}$ in (1) and $C_{l;k}$ denote the achievable rate for the signal to user $l$ at user $k$ with SIC in descending order, where $l \geq k$. Then, it can be shown that

$$C_{l;k} = \log_2 \left( 1 + \frac{\alpha_k P_l}{\alpha_k \sum_{m=1}^{l-1} P_m + 1} \right).$$  \hspace{1cm} (3)

Assume that user $k$ has to decode his/her signal (i.e., $\{s_{k,t}\}$) as well as the signals to user $l$, $l \in \{k, \ldots, K\}$ for SIC in NOMA. In this case, the rate-region can be found as

$$R_l < C_{l;k}, \ l \in \{k, \ldots, K\}, k \in \{1, \ldots, K\}. \hspace{1cm} (4)$$

Clearly, user $k$ should be able to decode the signals to users $k, \ldots, K$. As an example, suppose that $K = 2$. At user 1, the signal to user 2 can be decoded if

$$R_2 < C_{2;1} = \log_2 \left( 1 + \frac{\alpha_2 P_2}{\alpha_1 P_1 + 1} \right).$$

Once $\{s_{2,t}\}$ is decoded at user 1 and removed by SIC, $C_{1;1}$ becomes $\log_2 (1 + \alpha_1 P_1)$ and the signal to user 1 can be decoded if

$$R_1 < C_{1;1} = \log_2 (1 + \alpha_1 P_1). \hspace{1cm} (5)$$

At user 2, assuming that $\{s_{1,t}\}$ is sufficiently weaker than $\{s_{2,t}\}$, $\{s_{2,t}\}$ can be decoded if

$$R_2 < C_{2;2} = \log_2 \left( 1 + \frac{\alpha_2 P_2}{\alpha_2 P_1 + 1} \right). \hspace{1cm} (6)$$

If $\alpha_1 \geq \alpha_2$ is assumed, we have

$$\frac{\alpha_2 P_2}{\alpha_2 P_1 + 1} \leq \frac{\alpha_1 P_2}{\alpha_1 P_1 + 1} \text{ or } C_{2;2} \leq C_{2;1}. \hspace{1cm} (7)$$

Thus, the rate-region of $R_1$ and $R_2$ in (4) is reduced to

$$R_1 < C_{1;1} \text{ and } R_2 < C_{2;2}. \hspace{1cm} (8)$$

In general, for any $K \geq 2$, if

$$\alpha_1 \geq \ldots \geq \alpha_K,$$  \hspace{1cm} (9)

the rate-region in (4) is reduced to

$$R_l < C_{l;k}, \ l = 1, \ldots, K, \hspace{1cm} (10)$$

because $C_{l;k} \geq C_{l;l}$, $k \in \{1, \ldots, l-1\}$, $l \in \{1, \ldots, K\}$.

If the BS knows CSI and orders the users according to (7), we can consider a power allocation problem for downlink NOMA to maximize the sum rate subject to a total power constraint as follows:

$$\max_p \{ \sum_{k=1}^{K} C_{k;k} \} \text{ subject to } \sum_{k=1}^{K} P_k \leq P_T,$$  \hspace{1cm} (11)

where $p = [P_1, \ldots, P_K]^T$ and $P_T$ is the total transmission power. The power allocation problem in (9) has a trivial solution that is $P_1 = P_T$ and $P_k = 0$, $k = 2, \ldots, K$. To avoid this, rate constraints can be taken into account. To this end, we can consider another power allocation problem to minimize the total transmission power with rate constraints as follows:

$$\min_p \{ \|p\|_1 \} \text{ subject to } C_{k;k} \geq \bar{R}_k, \ k = 1, \ldots, K,$$  \hspace{1cm} (12)

where $\bar{R}_k$ represents the (required) minimum rate for user $k$ and $\|x\|_1 = \sum_i |x_i|$ denotes the 1-norm of vector $x$. This problem formulation can be employed instead of the approaches in [28] and [17] for fairness as each user can ensure
a guaranteed rate, \( R_1 \). In Appendix A, we provide the solution to (10).

For example, consider the case of \( K = 2 \) with \( \{ a_1, a_2 \} = \{ 1, 1/4 \} \). If we assume that \( P_T = 10 \), the rate-region of \( R_1 \) and \( R_2 \) can be obtained as in Fig. 1. We note that if \( P_1 = 10 \) and \( P_2 = 0 \), which is the solution to (9), the maximum sum rate (log\(_2\)(1 + \( a_1 P_T \)) = log\(_2\)(11) \( \approx \) 3.459) is achieved.

If we consider the problem in (10) with \( R_1 = 2 \) and \( R_2 = 1 \), we can first decide the minimum of \( P_1 \) satisfying \( C_{1,1} \geq R_1 = 2 \), because \( C_{1,1} \) is a function of only \( P_1 \) as in (5), which is \( P_1^* = 3 \). Once \( P_1^* \) is decided, we can find the minimum of \( P_2 \) satisfying \( C_{2,2} \geq R_2 = 1 \) from (6), which is \( P_2^* = 7 \). We can see that \( P_1^* + P_2^* = 10 \). Thus, the solution to (10) can be located on the boundary of the rate-region with \( P_T = 10 \) as shown in Fig. 1 (with the circle mark).

![Fig. 1. Rate-region for \( R_1 \) and \( R_2 \) when \( \{ a_1, a_2 \} = \{ 1, 1/4 \} \) and \( P_T = 10 \). The circle mark is the solution to (10) when \( R_1 = 2 \) and \( R_2 = 1 \).](image)

The above example demonstrates that the solution to (10) can be readily found if the BS knows the CSI, \( \{ a_k \} \). In addition, the solution can achieve the rate-region. Although the problem formulation in (10) is attractive, the main drawback is the CSI feedback. In [23], limited feedback of CSI is considered for a more realistic environment in NOMA. It is also possible to perform the power allocation for NOMA with statistical CSI. In this case, the outage probability is usually employed as a performance measure as in [17] [29] [30] [31].

Since most power allocation methods are based on the achievable rate, they may not be applicable when capacity achieving codes are not employed for NOMA. Furthermore, with fixed modulation schemes, it is not easy to adapt the transmission rates according to the optimal powers due to the limited flexibility. Thus, it is often desirable to consider the power allocation for a realistic NOMA system. To this end, the power allocation can be investigated for a practical MUST scheme as in [32].

IV. BEAMFORMING FOR DOWNLINK NOMA

To increase the spectral efficiency of downlink in a multiuser system, multiuser downlink beamforming can be considered. While there are various approaches for multiuser downlink beamforming without NOMA, only few beamforming schemes are studied with NOMA. For example, zero-forcing (ZF) approaches are considered in [2], [23] and random beams are used in [25], [26]. In [33], a minorization-maximization algorithm (MMA) is employed to maximize the sum rate in NOMA with beamforming. In [21], multi-cell MIMO-NOMA networks are studied with coordinated beamforming. In this section, we discuss NOMA beamforming that was studied in [2].

For downlink NOMA, we can exploit the power domain as well as the spatial domain to increase the spectral efficiency as in [2] [25]. In Fig. 2, we illustrate downlink beamforming for a system of 4 users. There are two clusters of users. Users 1 and 3 belong to cluster 1. In cluster 2, there are users 2 and 4. 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 [2]. The resulting approach is called NOMA (downlink) beamforming.

![Fig. 2. An illustration of NOMA with beamforming.](image)

In NOMA beamforming, there are two key problems. The first problem is user clustering. In general, a group of users whose channels are highly correlated can form a cluster. The second problem is beamforming. A beam is to support a set of users in a cluster, while this beam should not interfere with the users in the other clusters. As in [2], it is convenient to consider the two problems separately at the cost of degraded performance.

To consider NOMA beamforming, we focus on one cluster consisting of two users. We assume that user 1 is a strong user (close to the BS) and user 2 is a weak user (far away from the BS). The signal-to-interference-plus-noise ratio (SINR) at user 2 is given by

\[
\gamma_2 = \frac{|h_2|^2 w^2 P_2}{|h_2|^2 w^2 P_1 + \sigma^2},
\]

(11)

To keep a certain QoS, we need to satisfy \( \gamma_2 \geq G_2 \), where \( G_2 \) represents the target SINR at user 2 (it is assumed that if \( \gamma_2 \geq G_2 \), the signal to user 2 can be correctly decoded). As usual, user 2 is assumed to be a weak user that is far away from the BS. On the other hand, user 1, called a strong user,
is close to the BS and able to decode the signal to user 2 and remove it by SIC, and decode the desired signal (i.e., the signal to user 1). Thus, at user 2, it is required that
\[
\frac{|h_1^2w|^2p_2}{|h_1^2w|^2p_1 + \sigma^2} \geq G_2, \tag{12}
\]
and
\[
\gamma_1 = \frac{|h_1^2w|^2p_1}{\sigma^2} \geq G_1, \tag{13}
\]
where \(G_1\) represents the target SINR at user 1. Note that the sum rate of the cluster becomes \(\log_2(1 + G_1) + \log_2(1 + G_2)\). From (11) – (13), the following set of constraints can be found:
\[
|h_1^2w|^2 \geq |h_2w|^2, \tag{14}
\]
\[
|h_1^2w|^2p_1 \geq G_1\sigma^2, \tag{15}
\]
\[
|h_1^2w|^2p_2 \geq (|h_2^2w|^2p_1 + \sigma^2)G_2. \tag{16}
\]
Consequently, the problem to minimize the transmit power per cluster, \(P_1 + P_2\), can be formulated with the constraints in (14), (15), and (16).

It is possible to find the optimal beam that minimizes the transmission power subject to (14) - (16). With \(M = 3\) clusters, the optimal beam is found for different numbers of antennas. In Fig. 3, we show the required total transmission power to meet the quality of service (QoS) with target SINRs, \(G_1\) and \(G_2\). It is clear that NOMA requires a lower transmission power than orthogonal multiple access (OMA), while the required total transmission power decreases with the number of antennas \(L\) due to the beamforming gain.

![Graph showing the total transmission power for different values of the number of antennas, \(L\), when there are \(M = 3\) clusters with \((G_1, G_2) = (10 \text{ dB}, 6 \text{ dB})\).]

In addition to NOMA beamforming, the user allocation or clustering plays a crucial role in improving the performance. In [2] [25] [34], other beamforming approaches with user clustering are studied. It is noteworthy that the NOMA beamforming approach with user clustering is not optimal. For a better performance, without user clustering, as in [35], an optimization problem can be formulated. However, in this case, the computational complexity to find the optimal solution is usually high.

V. UPLINK NOMA

NOMA can be employed for uplink transmissions based on the coordination by the BS, which requires signaling overhead. It is also possible to consider uncoordinated uplink NOMA. In this section, we briefly discuss coordinated and uncoordinated uplink NOMA systems.

A. Coordinated Uplink NOMA

From (2), the mutual information between \(r_t\) and \(\{u_{k,t}\}\) is given by
\[
I(r_t; \{u_{k,t}\}) = \log_2 \left( 1 + \sum_{k=1}^{K} \beta_k Q_k \right), \tag{17}
\]
where \(\beta_k = |g_k|^2\) and \(Q_k = \mathbb{E}[|u_{k,t}|^2]\). In general, in order to achieve the rate \(I(r_t; \{u_{k,t}\})\) in (17), the BS may need to perform joint decoding for all \(K\) signals. However, using the chain rule [9], it is also possible to show that
\[
I(r_t; \{u_{k,t}\}) = \sum_{k=1}^{K} \log_2 \left( 1 + \frac{\beta_k Q_k}{1 + \sum_{l=1}^{K-1} \beta_l Q_l} \right). \tag{18}
\]
From this, we can clearly see that the BS can decode \(K\) signals sequentially and independently using SIC. For example, if \(K = 2\), we have
\[
I(r_t; \{u_{k,t}\}) = \log_2 \left( 1 + \frac{\beta_2 Q_2}{1 + \beta_1 Q_1} \right) + \log_2 \left( 1 + \beta_1 Q_1 \right).
\]
Thus, if user 2 transmits the coded signals at a rate lower than \(\log_2 \left( 1 + \frac{\beta_2 Q_2}{1 + \beta_1 Q_1} \right)\), the BS can decode the signals and remove them. Then, the BS can decode the coded signals from user 1 at a rate lower than \(\log_2 \left( 1 + \beta_1 Q_1 \right)\). This approach is considered to prove the capacity of multiple access channels [9], while CDMA and IDMA can be seen as certain implementation examples of uplink NOMA [36]. In [37], uplink NOMA is considered for multicarrier systems. For a given decoding order, the power allocation and subcarrier allocation are carried out to maximize the sum rate.

In practice, for uplink NOMA, the BS needs to know the CSI and decides the rates and powers according to a certain decoding order. In other words, there could be a lot of signaling overhead for uplink NOMA, which may offset the NOMA gain.

B. Uncoordinated Uplink NOMA: Random Access with NOMA

It is possible to employ uplink NOMA without coordination. To this end, we can consider random access, e.g., ALOHA [38]. In ALOHA, if there are \(K\) users and each of them transmits a packet with access probability \(p_a\), the throughput becomes
\[
T = Kp_a(1 - p_a)^{K-1}.
\]
For a sufficiently large $K$, the throughput can be maximized when $p_a = \frac{1}{K}$, and the maximum throughput becomes $e^{-1} \approx 0.3679$.

Suppose that uplink NOMA is employed and it is possible to decode up to two users if two users have two different power levels. Since there is no coordination, each user can choose one of two possible power levels. In this case, the throughput becomes

$$T = K p_a (1 - p_a)^{K-1} + \frac{1}{2} \binom{K}{2} p_a^2 (1 - p_a)^{K-2},$$

where the second term is the probability that there are two users transmitting packets and they choose different power levels. In Fig. 4, we show the throughput of ALOHA and the throughput of NOMA-ALOHA with 2 power levels when there are $K = 10$ users. It is clear that NOMA can improve the throughput of ALOHA.

![Fig. 4. Throughput of ALOHA and NOMA-ALOHA with 2 power levels when there are $K = 10$ users.](image)

We can generalize NOMA-ALOHA with multi-channels as in [39]. For example, as shown in Fig. 5, the both power and frequency domains can be considered to form multiple sub-channels for ALOHA. The throughput is shown in Fig. 6 when there are $K = 200$ users, $B = 6$ subcarriers, and $L = 4$ different power levels. It is noteworthy that the maximum throughput can be close to $B = 6$. In other words, NOMA-ALOHA can achieve a near full utilization of channels due to additional subchannels in the power domain. However, the transmission power increases as a user may choose a higher power than the required one without any MAI [39].

![Fig. 5. Power-Frequency domain resource blocks for multichannel ALOHA ($L = 2$ power levels and $B = 8$ (orthogonal) subcarriers).](image)

![Fig. 6. Throughput for different values of access probability, $p_a$, when $K = 200$, $L = 4$, and $B = 6$.](image)

by applying NOMA independently to a cluster consisting of few users provided that inter-cluster interference is mitigated (possibly using beamforming). Unfortunately, the performance degradation due to user clustering is not known, while its advantage to lower the complexity of downlink NOMA is clear. Another important topic to be studied is optimal user ordering in NOMA beamforming. Without the space domain (or beamforming), the optimal user ordering seems straightforward (it is usually based on the channel gains). However, when the space and power domains are to be jointly exploited in NOMA, optimal user ordering is not yet well studied.

As discussed above, although there are various issues to be addressed, we believe that NOMA will be indispensable in future cellular systems.

### VI. CONCLUDING REMARKS

In this paper, we presented an overview of NOMA as well as some recent results. We considered the power allocation and beamforming for downlink NOMA. We also discussed some key issues of uplink NOMA.

There are a number of topics that are not discussed in this paper, although they are important. One of them is user clustering. In general, user clustering is used to simplify NOMA domain

by applying NOMA independently to a cluster consisting of few users provided that inter-cluster interference is mitigated (possibly using beamforming). Unfortunately, the performance degradation due to user clustering is not known, while its advantage to lower the complexity of downlink NOMA is clear. Another important topic to be studied is optimal user ordering in NOMA beamforming. Without the space domain (or beamforming), the optimal user ordering seems straightforward (it is usually based on the channel gains). However, when the space and power domains are to be jointly exploited in NOMA, optimal user ordering is not yet well studied.

As discussed above, although there are various issues to be addressed, we believe that NOMA will be indispensable in future cellular systems.

### APPENDIX A

**SOLUTION TO (10)**

Under the assumption of (7), the minimum power to user 1 to satisfy $C_{1;1} \geq \bar{R}_1$ is given by

$$P_1^* = \frac{2\bar{R}_1 - 1}{\alpha_1}.$$  

While $P_1^*$ is the minimum power to guarantee the target rate for user 1, a higher power may eventually minimize the sum power. However, this is not the case. To see this, let $P_1 > P_1^*$. Then, we can show that $C_{k:k}$ with $P_1$, $k = 2, \ldots, K$, is lower
than that with $P_1^*$. For example, we can see that
\[
\log_2 \left( 1 + \frac{\alpha_2 P_2}{\alpha_2 P_1^* + 1} \right) < \log_2 \left( 1 + \frac{\alpha_2 P_2}{\alpha_2 P_1 + 1} \right).
\]
Thus, to minimize $\sum_k P_k$, the optimal power to user 1 has to be $P_1^*$. For given $P_1^*$, we can also find the minimum power to user 2 as follows:
\[
P_2^* = \min P_2 \text{ s.t. } C_{2,2} \geq \bar{R}_2.
\]
After some manipulations, we have
\[
P_2^* = (2^{\bar{R}_2} - 1) \left( \frac{P_1^* + 1}{\alpha_2} \right).
\]
This is also the minimum power to user 2 that results in the minimum MAI to users $k > 2$. Consequently, the minimum power for each user $k$ (or the solution to (10)) can be decided as
\[
P_k^* = (2^{\bar{R}_k} - 1) \left( \sum_{j=1}^{k-1} P_j^* + \frac{1}{\alpha_k} \right).
\]

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