Cooperative Non-Orthogonal Multiple Access in 5G Systems

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***Abstract*—Non-orthogonal multiple access (NOMA) has received considerable recent attention as a promising candidate for 5G systems. A key feature of NOMA is that users with better channel conditions have prior information about the messages of other users. This prior knowledge is fully exploited in this letter, where a cooperative NOMA scheme is proposed. The outage probability and diversity order achieved by this cooperative NOMA scheme are analyzed, and an approach based on user pairing is also proposed to reduce system complexity.**

***Index Terms*—Non-orthogonal multiple access (NOMA), cooperative multiple access, 5G communications.**

I. Introduction

NON-ORTHOGONAL MULTIPLE ACCESS (NOMA) is fundamentally different from conventional orthogonal multiple access (MA) schemes, as in NOMA multiple users are encouraged to transmit at the same time, code and frequency, but with different power levels [1]. In particular, NOMA allocates less power to users with better channel conditions, and these users can decode their own information by applying successive interference cancellation [2]. Consequently such users will know the messages intended to other users; such prior information can be exploited to improve performance, but this has not been considered in previous forms of NOMA [3], [4].

In this letter, a cooperative NOMA transmission scheme is proposed to fully exploit prior information available in NOMA systems. In particular, the use of the successive detection strategy at the receivers means that users with better channel conditions need to decode the messages of the others, and therefore these users can be used as relays to improve the reception reliability for users with poor connections to the base station. Local short-range communication techniques, such as Bluetooth and ultra-wideband (UWB), can be used to deliver messages from the users with better channel conditions to those with poor channel conditions. The outage probability and diversity order achieved by this cooperative NOMA scheme are analyzed, and these analytical results demonstrate that cooperative NOMA can achieve the maximum diversity gain for all the users. In practice, inviting all users in the network to participate in cooperative NOMA might not be realistic due to the system complexity for coordinating user cooperation. User pairing is a promising solution to reduce system complexity, and we demonstrate that grouping users with high channel quality does not necessarily yield a large performance gain over orthogonal MA. Instead, it is preferable to pair users whose channel gains, the absolute squares of the channel coefficients, are more distinctive.

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II. System Model

Consider a broadcast channel with one base station (the source), and K users (the destinations). Cooperative NOMA consists of two phases, as described in the following.

A. Direct Transmission Phase

During this phase, the base station sends K messages to the destinations based on the NOMA principle, i.e., the base station sends $\sum_{m=1}^{K} p_m s_m$, where s_m is the message for the m-th user, and p_m is the power allocation coefficient for that user. The observation at the k-th user is given by $y_{1,k} = \sum_{m=1}^{K} h_k p_m s_m + n_k$, where h_k denotes the Rayleigh fading channel coefficient from the base station to the k-th user and n_k denotes additive Gaussian noise. Without loss of generality, assume that the users are ordered based on their channel quality, i.e.,

$$|h_1|^2 \leq \cdots \leq |h_K|^2. \tag{1}$$

The use of NOMA implies $|p_1|^2 \geq \cdots \geq |p_K|^2$, with $\sum_{m=1}^{K} p_m^2 = 1$. Successive detection will be carried out at the K-th user at the end of this phase. The received signal to interference plus noise ratio (SINR) for the K-th ordered user to detect the k-th user's message, $1 \leq k < K$, is given by

$$SINR_{K,k} = \frac{|h_K|^2 |p_k|^2}{\sum_{m=k+1}^{K} \left|h_K^H p_m\right|^2 + \frac{1}{\rho}}, \tag{2}$$

where ρ is the transmit SNR. After these users' messages are decoded, the K-th user can decode its own information with the SNR of $SNR_{K,K} \triangleq SINR_{K,K} = \rho |h_K|^2 |p_K|^2$. The conditions under which the K-th user can decode its own information are given by $\log(1 + SINR_{K,k}) > R_k$, $\forall 1 \leq k \leq K$, where R_k denotes the k-th user's targeted data rate.

B. Cooperative Phase

During this phase, the users cooperate with each other via short range communication channels.[1] Particularly the second phase consists of $(K-1)$ time slots. During the first time slot, the

[1] Without using short range communications, extra time slots are needed during the cooperative phase. The performance of cooperative NOMA without using short range communications will be studied in Section IV in comparison with non-cooperative NOMA, non-cooperative and cooperative conventional orthogonal MA.

K-th user broadcasts the combination of the $(K-1)$ messages with the coefficients $\mathbf{q}_K$, i.e., $\sum_{m=1}^{K-1} q_{K,m}s_m$ and $\sum_{m=1}^{K-1} q_{K,m}^2=1$, where $\sum_{m=1}^{K-1} q_{K,m}^2 = 1$. The k-th user observes the following:

$$y_{2,k} = \sum_{m=1}^{K-1} g_{K,k}q_{K,m}s_m + n_{2,k}, \tag{3}$$

for $k<K$, where $g_{K,k}$ denotes the inter-user channel coefficient. The $(K-1)$-th user uses maximum ratio combining to combine the observations from both phases, and the SINR for this user to decode the k-th user's message, $k < (K-1)$, is given by

$$SINR_{K-1,k} = \frac{|h_{K-1}|^2p_k^2}{|h_{K-1}|^2\sum_{m=k+1}^K p_m^2+\frac{1}{\rho}} + \frac{|g_{K,K-1}|^2q_{K,k}^2}{|g_{K,K-1}|^2\sum_{m=k+1}^{K-1} q_{K,m}^2+\frac{1}{\rho}}. \tag{4}$$

After the $(K-1)$-th user decodes the other users' messages, it can decode its own information with the following SINR:

$$SINR_{K-1,K-1} = \frac{|h_{K-1}|^2p_{K-1}^2}{|h_{K-1}|^2p_K^2+\frac{1}{\rho}} + |g_{K,K-1}|^2q_{K,K-1}^2. \tag{5}$$

Similarly in the n-th time slot, $1\leq n\leq(K-1)$, the $(K-n+1)$-th user broadcasts the combination of the $(K-n)$ messages with the coefficients $q_{K-n+1,m}$, i.e., $\sum_{m=1}^{K-n} q_{K-n+1,m}s_m$. The k-th user, $k<(K-n+1)$, observes

$$y_{2,k} = \sum_{m=1}^{K-n} g_{K-n+1,k}^H q_{K-n+1,m}s_m + n_{n+1,k}. \tag{6}$$

Combining the observations from both phases, the $(K-n)$-th user can decode the k-th user's message, $1\leq k<(K-n)$, with the following SINR:

$$SINR_{K-n,k} = \frac{|h_{K-n}|^2p_k^2}{|h_{K-n}|^2\sum_{m=k+1}^K p_m^2+\frac{1}{\rho}} + \sum_{i=1}^{n}\frac{|g_{K-i+1,K-n}|^2q_{K-i+1,k}^2}{|g_{K-i+1,K-n}|^2\sum_{m=k+1}^{K-i} q_{K-i+1,m}^2+\frac{1}{\rho}}, \tag{7}$$

and it can decode its own information with the following SINR:

$$SINR_{K-n,K-n} = \frac{|h_{K-n}|^2p_{K-n}^2}{|h_{K-n}|^2\sum_{m=K-n+1}^K p_m^2+\frac{1}{\rho}} + \sum_{i=1}^{n-1}\frac{|g_{K-i+1,K-n}|^2q_{K-i+1,K-n}^2}{|g_{K-i+1,K-n}|^2\sum_{m=K-n+1}^{K-i} q_{K-i+1,m}^2+\frac{1}{\rho}} + \rho|g_{K-n+1,K-n}|^2q_{K-n+1,K-n}^2. \tag{8}$$

Recall that, without cooperation, the SINR at the k-th user is $\frac{|h_{K-n}|^2p_{K-n}^2}{|h_{K-n}|^2\sum_{m=K-n+1}^K p_m^2+\frac{1}{\rho}}$. Comparing this to (8), one can see that the use of cooperation can boost reception reliability.

III. Performance Analysis

Provided that the $(n-1)$ best users can achieve reliable detection, the outage probability for the $(K-n)$-th user can be expressed as follows:

$$\mathrm{P}_o^{K-n} \triangleq \mathrm{P}\left(SINR_{K-n,k}<\epsilon_k,\ \forall k\in\{1,\cdots,K-n\}\right), \tag{9}$$

where $\epsilon_k = 2^{R_k}-1$. Note that the use of local short-range communications does not reduce the data rate. For notational simplicity, define $a_{k,i}^{K-n} = q_{K-i+1,k}^2$ and $b_{k,i}^{K-n} = \sum_{m=k+1}^{K-i} q_{K-i+1,m}^2$, where $1\leq k\leq(K-n)$ and $1\leq i\leq n$ with the special case of $a_{K-n,n}^{K-n} = q_{K-n+1,K-n}^2$ and $b_{K-n,n}^{K-n}=0$. In addition, define $a_{k,0}^{K-n}=p_k^2$ and $b_{k,0}^{K-n}=\sum_{m=k+1}^K p_m^2$, for $1\leq k\leq(K-n)$. By using the definition of the outage probability, we have the following proposition concerning the diversity order achieved by the proposed cooperative NOMA scheme.

Proposition 1: Assume that the $(n-1)$ best users can achieve reliable detection. The proposed cooperative NOMA scheme can ensure that the $(K-n)$-th ordered user experiences a diversity order of K, conditioned on $\epsilon_k < \frac{a_{k,i}^{K-n}}{b_{k,i}^{K-n}}$, for $1\leq k\leq(K-n)$ and $0\leq i\leq n$.

Proof: For notational simplicity, define $z_{k,i}^{K-n} = \frac{|g_{K-i+1,K-n}|^2q_{K-i+1,k}^2}{|g_{K-i+1,K-n}|^2\sum_{m=k+1}^{K-i}q_{K-i+1,m}^2+\frac{1}{\rho}}$, where $1\leq k\leq(K-n)$ and $1\leq i\leq n$, except $z_{K-n,n}^{K-n}=\rho|g_{K-n+1,K-n}|^2q_{K-n+1,K-n}^2$. In addition, define $z_{k,0}^{K-n}=\frac{|h_{K-n}|^2p_k^2}{|h_{K-n}|^2\sum_{m=k+1}^K p_m^2+\frac{1}{\rho}}$. The SINRs can be expressed as follows:

$$SINR_{K-n,k} = z_{k,0}^{K-n} + \sum_{i=1}^{n} z_{k,i}^{K-n}, \tag{10}$$

for $1\leq k\leq(K-n)$. Therefore the outage probability can be rewritten as follows:

$$\mathrm{P}_o^{K-n} = \mathrm{P}\left(z_{k,0}^{K-n}+\sum_{i=1}^{n}z_{k,i}^{K-n}<\epsilon_k,\ \forall k\in\{1,\cdots,K-n\}\right) \leq \sum_{k=1}^{K-n}\mathrm{P}\left(z_{k,0}^{K-n}+\sum_{i=1}^{n}z_{k,i}^{K-n}<\epsilon_k\right), \tag{11}$$

since $\mathrm{P}(A\cup B)\leq \mathrm{P}(A)+\mathrm{P}(B)$. Because channel gains are independent and $\mathrm{P}(a+b<c)\leq\mathrm{P}(a<c)+\mathrm{P}(b<c)$, the outage probability can be further bounded as follows:

$$\mathrm{P}_o^{K-n} \leq \sum_{k=1}^{K-n}\prod_{i=0}^{n}\mathrm{P}\left(z_{k,i}^{K-n}<\epsilon_k\right). \tag{12}$$

All the elements in (10) except $z_{k,0}^{K-n}$ and $z_{K-n,n}^{K-n}$ share the same structure as follows:

$$z_{k,i}^{K-n} = \frac{a_{k,i}^{K-n}x}{b_{k,i}^{K-n}x+\frac{1}{\rho}}. \tag{13}$$

When x is exponentially distributed, the cumulative distribution function (CDF) of $z_{k,i}^{K-n}$ is given by

$$\mathrm{P}_{z_{k,i}^{K-n}}(Z<z) = \begin{cases} 1, & \text{if } z\geq\frac{a_{k,i}^{K-n}}{b_{k,i}^{K-n}} \\ 1-e^{-\frac{z}{\rho\left(a_{k,i}^{K-n}-b_{k,i}^{K-n}z\right)}}, & \text{otherwise,}\end{cases} \tag{14}$$

where the definitions for the coefficients $a_{k,i}^{K-n}$ and $b_{k,i}^{K-n}$ are given in the proposition.

At high SNR, $\frac{\epsilon_k}{\rho\left(a_{k,i}^{K-n}-b_{k,i}^{K-n}z\right)}$ approaches 0, and the probability of the event, $z_{k,i}^{K-n} < \epsilon_k$, can be approximated by using the power series of exponential functions [5] as follows:

$$\mathrm{P}_{z_{k,i}^{K-n}}(Z < \epsilon_k) = 1 - e^{-\frac{\epsilon_k}{\rho\left(a_{k,i}^{K-n}-b_{k,i}^{K-n}\epsilon_k\right)}} \approx \frac{\epsilon_k}{\rho a_{k,i}^{K-n}}, \tag{15}$$

which is conditioned on $\epsilon_k < \frac{a_{k,i}^{K-n}}{b_{k,i}^{K-n}}$.

The distribution functions of the two special cases, $z_{k,0}^{K-n}$ and $z_{K-n,n}^{K-n}$, can be obtained as follows. Note that the source-user channels are sorted according to their quality. By applying order statistics [6], the CDF of $z_{k,0}^{K-n}$ can be found as follows:

$$\mathrm{P}_{z_{k,0}^{K-n}}(Z < z) = \begin{cases} 1, & \text{if } z \geq \frac{a_{k,0}^{K-n}}{b_{k,0}^{K-n}} \\ \int_0^{\frac{\frac{z}{\rho}}{a_{k,0}^{K-n}-b_{k,0}^{K-n}z}} \frac{e^{-x}}{(K-n-1)!}x^{K-n-1}dx, & \text{otherwise}, \end{cases} \tag{16}$$

Again applying the high SNR approximation, the probability, $\mathrm{P}(z_{k,0}^{K-n} < \epsilon_k)$, can be approximated by using the power series of exponential functions [5] as follows:

$$\mathrm{P}\left(z_{k,0}^{K-n} < \epsilon_k\right) = \int_0^{\frac{\epsilon_k}{\rho\left(a_{k,i}^{K-n}-b_{k,i}^{K-n}\epsilon_k\right)}} \frac{x^{K-n-1}e^{-x}}{(K-n-1)!}dx \approx \frac{\epsilon_k^{K-n}}{(K-n)!\left(a_{k,i}^{K-n}\right)^{K-n}\rho^{K-n}}, \tag{17}$$

conditioned on $\epsilon_k < \frac{a_{k,0}^{K-n}}{b_{k,0}^{K-n}}$. Similarly the probability for the event $z_{K-n,n}^{K-n} < \epsilon_k$ can be approximated as follows:

$$\mathrm{P}\left(z_{K-n,n}^{K-n} < \epsilon_k\right) \approx \frac{\epsilon_k}{q_{K-n+1,K-n}^2\rho}, \tag{18}$$

since $z_{K-n,n}^{K-n}$ can be treated as a special case of (13).

Combining (12), (15), (17) and (18), the diversity order achieved by the cooperative NOMA scheme can be obtained, which completes the proof. □

The overall system outage event is defined as the event that any user in the system cannot achieve reliable detection, which means the overall outage probability is defined as follows:

$$\mathrm{P}_o \triangleq 1 - \prod_{k=1}^{K}\left(1 - \mathrm{P}_o^k\right). \tag{19}$$

By using Proposition 1 and the independence among the channels, the following lemma can be obtained straightforwardly.

Lemma 1: The proposed cooperative NOMA scheme ensures that the n-th best user, $1 \leq n \leq K$, experiences a diversity order of K, conditioned on $\epsilon_k < \frac{a_{k,i}^{K-n}}{b_{k,i}^{K-n}}$, for $1 \leq k \leq (K-n)$ and $0 \leq i \leq n$.

This diversity order result is not surprising as explained in the following. Take the user with the worst channel connection to the source as an example. When cooperative NOMA is implemented, this user gets help from the other $(K-1)$ users, in addition to its own direct channel to the source. In general, cooperative NOMA can efficiently exploit user cooperation and ensure that a diversity order of K is achievable by all users, regardless of their channel conditions, whereas non-cooperative NOMA can achieve only a diversity order of n for the n-th ordered user [4].

Reducing System Complexity Via User Pairing: Practical implementation of cooperative NOMA may face some challenges, which motivates the study of user pairing/grouping. Particularly it is more practical to divide the users in one cell into multiple groups, where cooperative NOMA is implemented within each group and conventional MA can be used for inter-group multiple access. Since there are fewer users in each group to participate in cooperative NOMA in this hybrid MA system, the aforementioned challenges can be effectively mitigated. Without loss of generality, we focus on the case of selecting only two users. An important question to be answered here is which two users should be grouped together.

Assume that the users are ordered as (1), and the m-th and n-th users are paired together, $m < n$. The conventional time division multiple access (TDMA) can achieve the following rates: $\bar{R}_i = \frac{1}{2}\log(1+\rho|h_i|^2)$, $i \in \{m, n\}$. The rates achieved by cooperative NOMA are quite complicated, so we first consider conventional NOMA which can achieve the following rates: $R_m = \log\left(1 + \frac{\rho|h_m|^2p_m^2}{\rho|h_m|^2p_n^2+1}\right)$, and $R_n = \log\left(1+\rho p_n^2|h_n|^2\right)$, where R_n is achievable since $\log\left(1+\frac{|h_n|^2p_m^2}{|h_n|^2p_n^2+1}\right) \geq R_m$.

The gap between the sum rates achieved by TDMA and conventional NOMA can be expressed at high SNR as follows:

$$R_m + R_n - \bar{R}_m - \bar{R}_n \approx \log\left(1+\frac{p_m^2}{p_n^2}\right) + \log\rho p_n^2|h_n|^2 - \frac{\log\rho|h_m|^2}{2} - \frac{\log\rho|h_n|^2}{2} = \frac{\log|h_n|^2}{2} - \frac{\log|h_m|^2}{2}. \tag{20}$$

It is interesting to observe that the gap is not a function of the power allocation coefficients p_m, but rather depends on how different the two users' channels are. Therefore for conventional NOMA, the worst choice of m and n is $n = m+1$, and it is ideal to group two users who experience significantly different channel fading. This observation is also valid for cooperative NOMA. Particularly an important observation from (2) is that the data rate for the m-th user is bounded as $R_m \leq \log\left(1+\frac{\rho|h_n|^2p_m^2}{\rho|h_n|^2p_n^2+1}\right)$, although R_m can be as large as $\log\left(1+\frac{\rho|h_m|^2p_m^2}{\rho|h_m|^2p_n^2+1}+\rho|g_{n,m}|^2\right)$, where the bound is due to the fact that the n-th user needs to decode the m-th user's information. Since $\log\left(1+\frac{\rho|h_n|^2p_m^2}{\rho|h_n|^2p_n^2+1}\right) \approx \log\left(1+\frac{p_m^2}{p_n^2}\right)$, the conclusion obtained for conventional NOMA can also be applied to cooperative NOMA. Further details about user pairing for non-cooperative NOMA can be found in [7].

IV. Numerical Studies

In Fig. 1, the outage probabilities achieved by the three schemes, e.g., orthogonal MA, non-cooperative NOMA, and cooperative NOMA, are shown as functions of SNR, with $K=2$ and $p_1^2 = \frac{4}{5}$. As can be seen from the figure, cooperative NOMA outperforms the other two schemes, since it can ensure that the maximum diversity gain is achievable by all the users as indicated by Lemma 1. In Fig. 2, the outage capacities achieved by the three schemes are shown, by setting $R_1 = R_2$. The vertical axis of the figure corresponds to $(1-\mathrm{P}^o)$, i.e., one minus the outage probability, given the targeted data rate specified along the horizontal axis. For example, with 10% outage probability

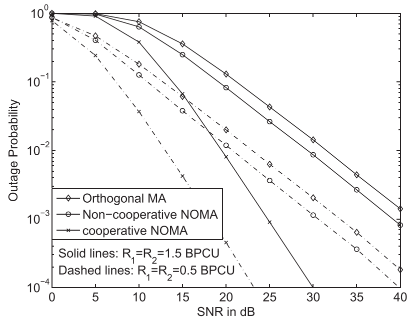

Fig. 1. Outage probability achieved by cooperative NOMA.

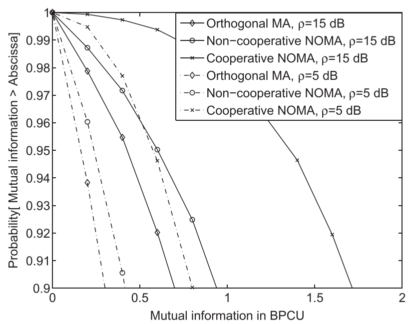

Fig. 2. Outage capacity achieved by cooperative NOMA.

and the transmit SNR equal to 15 dB, the orthogonal MA scheme can achieve a rate of 0.7 bits per channel use (BPCU), non-cooperative NOMA can support 0.95 BPCU, and cooperative NOMA can support 1.7 BPCU, much larger than the other two schemes.

Without using local short-range communications, cooperative MA schemes can be revised as follows. Consider an example with two users, in which the users' channels are ordered as in (1). For cooperative orthogonal MA, the first two time slots are allocated to the two users, respectively, the same as in non-cooperative orthogonal MA, and one additional time slot is consumed because of user cooperation, which means that three time slots are used in total. Similarly for cooperative NOMA, the base station serves the two users simultaneously during the first two time slots, and one additional time slot is required by User 2 to help User 1. Because different numbers of time slots are used for the two phases, we consider the situation in which the relay uses a codebook independent of the one at the source, for both cooperative MA schemes. By applying [2, Theorem 15.7.2], one can find that, when $R_1 < \frac{2}{3}\log(1+SINR_{2,1})$, i.e., User 2 can decode User 1's message correctly, the achievable rate at User 1 is $\frac{1}{3}\left(2\log(1+SINR_{1,1})+\log(1+\rho|g_{2,1}|^2)\right)$ and the achievable rate at User 2 is $\frac{2}{3}\log(1+SINR_{2,2})$. The cases for cooperative orthogonal MA can be obtained similarly. Fig. 3 demonstrates that cooperative NOMA can still outperform the comparable schemes, particularly at high SNR.

Fig. 4 demonstrates the impact of user pairing on both cooperative and non-cooperation scenarios. Suppose that the K-th ordered user, i.e., the user with the best channel condition, is scheduled, and Fig. 4 demonstrates how large a sum rate gain can be obtained by pairing it with different users. Scheduling the user with the worst channel can provide a sum rate gain of 1.5 BPCU at 10 dB, whereas a gain of 0.2 BPCU is achieved by scheduling the user with the second best channel. This observation is consistent with the discussions in Section III, where without careful user scheduling, the benefit of using NOMA diminishes.

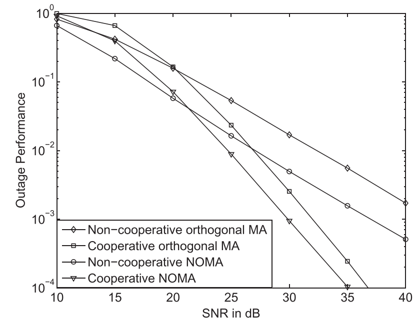

Fig. 3. Outage probability achieved by cooperative NOMA without using local short-range communications. $R_1 = 1.2$ BPCU and $R_2 = 1.9$ BPCU.

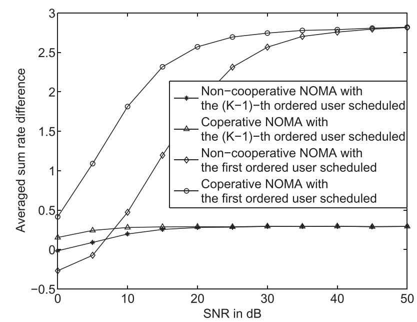

Fig. 4. The impact of user pairing on the sum rate. $K = 10$.

V. Conclusion

In this letter, we have proposed a cooperative NOMA transmission scheme which uses the fact that some users in NOMA systems have prior information about the others' messages. Analytical results have been developed to demonstrate the performance gain of this cooperative NOMA scheme. Fixed choices of power allocation coefficients have been used in this letter, and it is important to study optimal power allocation for cooperative NOMA [8], [9]. Another promising future direction is to apply simultaneous wireless information and power transfer to NOMA in order to alleviate practical constraints on energy consumption.

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