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Mode Selection Between Index Coding and Superposition Coding in Cache-based NOMA Networks

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***Abstract*—By analytically showing that index coding (IC) is more power efficient than superposition coding (SC) when appropriate caching contents are available for a pair of users, we propose a sub-optimal joint user clustering and power allocation scheme for a single-cell downlink non-orthogonal multiple access (NOMA) network with caching memory at the receivers that alternates between IC and SC. Simulation studies demonstrate that the proposed scheme significantly reduces the transmission power when compared to the benchmark scheme that only allows SC.**

***Index Terms*—Caching, index coding (IC), NOMA, optimal power control, superposition coding (SC), user clustering.**

I. Introduction

Non-orthogonal multiple access (NOMA) accommodates multiple access from new perspective, i.e., NOMA allows multiple users with discrepant power levels to share the same time/frequency resource block simultaneously. Thus, NOMA can provide higher spectrum efficiency and more freedom of connectivity than conventional orthogonal multiple access (OMA) schemes. Even though the basic principles behind NOMA have been around for decades of years, the conception about the application of NOMA in practical wireless systems was proposed by Saito *et al.* in 2013 [1], since then NOMA has been intensively studied from various aspects [2].

Cache-based NOMA becomes one of the research hotspots since it was shown by Ding *et al.* [3] that cache can help to further enhance the spectral efficiency of NOMA systems. Besides, Zhao *et al.* in [4] demonstrated that content caching based NOMA achieves better coverage performance than OMA schemes. All the existing cache aided NOMA works adopted superposition coding (SC) at transmitters. However, for certain cached scenario, index coding (IC) is more power efficient than SC. Therefore, in this work, we investigate the potential gains of applying IC in cache assisted NOMA, where the transmission mode of BS is either SC or IC in accordance with the cached information at users.

The main contributions are summarized as follows: *First*, we propose a new transmission mechanism for cache based NOMA, where either IC or SC is applied at BS. *Second*, we formulate the joint user clustering and power control problem as a hybrid integer programming problem. To solve the non-linear integer problem, a two-step methodology is designed. In Step one, we determine the user clustering strategy. To reduce the computational complexity of the optimal exhaustive search method, a suboptimal strategy is designed based on the cached information and link gain difference among users. With the given user clustering manner, we show that the resultant power control problem is standard in Step two, which can be optimally solved in an iterative manner.

II. System Model

A. System Descriptions

The scenario that a BS delivers K distinct packets to K users is considered. We assume each packet has the same number of bits. Let $\mathcal{K} \triangleq \{1, 2, \ldots, K\}$ be the index set that represents the indices of both packets and users. Besides, for $i \in \mathcal{K}$, denote by s_i the i-th packet. We assume that all the users have the capability of caching, which means each user has prior information of some packets. Let $\mathcal{S}_k \subseteq \mathcal{K} \setminus \{k\}$ be the index set of the cached packets at user k. For example, if $\mathcal{S}_k = \{3, 4\}$, user k already has packets s_3 and s_4 in its cache. Besides, we assume each user is equipped with a cache unit with capacity C, i.e., $|\mathcal{S}_k| \leq C$ for $k \in \mathcal{K}$.

In downlink NOMA system, successive interference cancellation (SIC) is adopted at receivers. However, a large number of multiplexed users induce to high complexity of receivers. Therefore, we apply pairing to separate users into different clusters where each cluster has two users for simplicity[1] [5]. SIC is adopted within each cluster. Note that K is assumed to be an even number, and $K/2$ clusters are used to serve all the users. Define $\mathcal{N} = \{1, 2, \ldots, K/2\}$ as the index set of all clusters. Besides, let $\mathcal{U}_n$ be the users indices in cluster n. Moreover, for $n \in \mathcal{N}$, let X_n be the signal[2] transmitted at BS for users in $\mathcal{U}_n$ and Y_l be the received signal of user $l \in \mathcal{U}_n$. Therefore, we have

$$Y_l = \sqrt{g_l} X_n + \sqrt{g_l} \tilde{X}_l + N_l, \quad (1)$$

where g_l is the link gain between BS to user l. Without loss of generality, we assume $g_i < g_j$ if $i < j$. $\tilde{X}_l$ and N_l represent

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[1]For the multi-user per cluster scenarios, the major difference lies in the number of possible caching cases, which can be analyzed by following a similar method in Subsections II-C and III-B.

[2]For $n \in \mathcal{N}$, X_n could be the signal generated by superposition coding or by index coding. Details will be discussed later in this work.

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the received signal of the other clusters at user l and the additive Gaussian random noise signal, respectively. Assume N_l has mean zero and variance η. For notational simplicity, we define the normalized noise power at user k as $\eta_k \triangleq \eta/g_k$ for $k \in \mathcal{K}$. Moreover, for $k \in \mathcal{K}$, we assume user k has a minimum data rate requirement, $\bar{R}_k$, which is in one-to-one correspondence to the minimum signal-to-interference-plus-noise (SINR) threshold of user k, i.e., $\gamma_k = 2^{\bar{R}_k/W} - 1$, where W indicates the system bandwidth.

B. Transmission Mechanism at BS

In this subsection, the transmission mechanism at BS is introduced. For $k \in \mathcal{K}$, let s_k be the packet to be sent to user k. Besides, define p_k as the transmit power of packet k. There is an encoder function, say enc$(\cdot)$, such that the coded packet of user k is given as $Z_k = \text{enc}(s_k)$, where enc(s_k) is assumed to be a random variable with unit variance and zero mean. Moreover, we adopt a binary variable $c_{i,j} \in \{0, 1\}$ to show whether users i and j are paired, where $i \neq j$. Specifically, $c_{i,j} = 1$ if and only if users i and j are assigned in the same cluster. Let $\boldsymbol{c} = (c_{1,2}, c_{1,3}, \ldots, c_{K,K-1})$ be the user clustering indicator vector of the system. Without loss of generality, we assume $\mathcal{U}_n = \{i, j\}$, where $i < j$. The two transmission schemes are stated below:

1) Superposition Coding (SC): For SC, the transmitted signal for users in cluster n is

$$\begin{aligned} X_n &= \sqrt{p_i} \cdot \text{enc}(s_i) + \sqrt{p_j} \cdot \text{enc}(s_j) \\ &= \sqrt{p_i} Z_i + \sqrt{p_j} Z_j, \end{aligned} \tag{2}$$

According to (1), the received signals at users i and j are

$$\begin{aligned} Y_i &= \sqrt{g_i}(\sqrt{p_i} Z_i + \sqrt{p_j} Z_j) + \sqrt{g_i}\tilde{X}_i + N_i, \\ Y_j &= \sqrt{g_j}(\sqrt{p_i} Z_i + \sqrt{p_j} Z_j) + \sqrt{g_j}\tilde{X}_j + N_j. \end{aligned} \tag{3}$$

Incidentally, with the above stated, the normalized inter-cluster interference plus noise power at user l who is associated to cluster n is obtained as follows:

$$I_l = \sum_{n'=1, n' \neq n}^{|\mathcal{N}|} P_{n'} + \eta_l, \tag{4}$$

in which $P_{n'}$ is the transmit power of cluster n'.

2) Index Coding (IC): If IC is adopted, the transmitted signal of cluster n is $X_n = \sqrt{P_{IC}} \cdot \text{enc}(s_i \oplus s_j)$, where $\oplus$ is the bit-wise binary addition, and P_{IC} indicates the transmit power. Similarly, the received signals at two users are

$$\begin{aligned} Y_i &= \sqrt{g_i}(\sqrt{P_{IC}} \cdot \text{enc}(s_i \oplus s_j)) + \sqrt{g_i}\tilde{X}_i + N_i, \\ Y_j &= \sqrt{g_j}(\sqrt{P_{IC}} \cdot \text{enc}(s_i \oplus s_j)) + \sqrt{g_j}\tilde{X}_j + N_j. \end{aligned} \tag{5}$$

An auxiliary variable $a_{i,j} \in \{0, 1\}$ is introduced to show whether user i caches the desired packet of user j, i.e., $a_{i,j} = 1$ if and only if $j \in \mathcal{S}_i$. Similarly, we define $a_{j,i}$ for user j. With the aforementioned definitions, we are restricting ourselves to the following rules when considering the transmission mechanism at BS: we adopt IC if $a_{i,j} = 1$ and $a_{j,i} = 1$ and SC otherwise. The reason is explained in the following Theorem:

Theorem 1. *If $a_{i,j} = 1$ and $a_{j,i} = 1$, the required power for users to satisfy their minimum data rate constraints with IC is smaller than that with SC.*

Proof: First, we consider the case where SC is applied at BS. Since both users i and j cache the prior information of the other user, at receiver sides, the achievable data rates of two users are $\hat{R}_i = W \log_2(1 + \frac{p_i}{I_i})$ and $\hat{R}_j = W \log_2(1 + \frac{p_j}{I_j})$, respectively. To satisfy the minimum data rate constraints: $\hat{R}_i \geq \bar{R}_i$ and $\hat{R}_i \geq \bar{R}_j$, the least required power is $P_{SC} = \gamma_i I_i + \gamma_j I_j$.

Then, we see the IC case. In the case of IC, the XOR operation is applied to packets i and j to formed a coded packet. Both users decode this packet first. Afterwards, each user performs XOR between the decoded packet and the packet in his cache to obtain his requested packet. As a result, the obtained data rates are $\hat{R}_i = W \log_2(1 + \frac{P_{IC}}{I_i})$ and $\hat{R}_j = W \log_2(1 + \frac{P_{IC}}{I_j})$, respectively. It is easy to calculate that the minimum required power for satisfying the data rate requirements with IC is $P_{IC} = \max\{\gamma_i I_i, \gamma_j I_j\}$. The proof is completed since $P_{SC} - P_{IC} = \min\{\gamma_i I_i, \gamma_j I_j\} > 0$. □

C. Capacity of Each User

With the proposed transmission mechanism, the achievable data rate of each user is analyzed in this subsection. For illustration, we take cluster n as an example. For $n \in \mathcal{N}$, let $\boldsymbol{P}_{-n} = (P_1, P_2, \ldots, P_{n-1}, P_{n+1}, \ldots, P_{|\mathcal{N}|})$. Given the value of $\boldsymbol{P}_{-n}$ and the user clustering indicator vector $\boldsymbol{c}$, the capacity of each user can be discussed by partitioning into the following three cases:

Case 1: $a_{i,j} = 0$, $a_{j,i} = 0$ or $a_{i,j} = 0$, $a_{j,i} = 1$. In this case, SC is adopted, and user j applies SIC. The capacity of users i and j is given as

$$\hat{R}_i = W \log_2(1 + \frac{p_i}{p_j + I_i}), \text{ and } \hat{R}_j = W \log_2(1 + \frac{p_j}{I_j}),$$

in which I_l, $l \in \mathcal{U}_n$ is given in (4).

Case 2: $a_{i,j} = 1$, $a_{j,i} = 0$. In this case, SC is also used. Since user i has packet j in his cache, user i can subtract packet j from his received signal. The achievable data rate of user i is then quoted below:

$$R'_i = W \log_2(1 + \frac{p_i}{I_i}). \tag{6}$$

For user j, SIC is applied. Specifically, user j first decodes the packet of user i, subtracting this packet from its received signal and then decodes its own packet. The capacity of user j to decode the packet of user i when performing SIC and the achievable data rate of user j are respectively given by

$$R''_i = W \log_2(1 + \frac{p_i}{p_j + I_j}), \tag{7}$$

$$\hat{R}_j = W \log_2(1 + \frac{p_j}{I_j}). \tag{8}$$

Based on (6) and (7), we have $\hat{R}_i = \min\{R'_i, R''_i\}$.

Case 3: $a_{i,j} = 1$, $a_{j,i} = 1$. In this case, IC is used. As shown in the proof of Theorem 1, we have $\hat{R}_i = W \log_2(1 + \frac{P_{IC}}{I_i})$ and $\hat{R}_j = W \log_2(1 + \frac{P_{IC}}{I_j})$.

Let $\boldsymbol{P} = (P_1, P_2, \ldots, P_N)$ be the power vector of all clusters. Define $\boldsymbol{a}$ as the caching information indicator vector of the system. With above mentioned analysis, we conclude the capacity of user k as $R_k = \hat{R}_k(\boldsymbol{a}, \boldsymbol{c}, \boldsymbol{P})$, where $k \in \mathcal{K}$.

D. Problem Formulation

We target at minimizing the total transmit power of the BS in consideration of each user's data rate constraint. The

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optimization problem can be formulated as

$$\min \sum_{n\in\mathcal{N}} P_n, \tag{9}$$

$$\begin{aligned} s.t.\ \ & C1: R_k \geq \bar{R}_k,\ k\in\mathcal{K},\\ & C2: P_n \geq 0,\ n\in\mathcal{N},\\ & C3: \sum_{j\neq i, j\in\mathcal{K}} c_{i,j}=1,\ i\in\mathcal{K},\\ & C4: c_{i,j}\in\{0,1\},\ i\in\mathcal{K},\ j\in\mathcal{K},\ j\neq i, \end{aligned} \tag{10}$$

where $C1$ indicates the minimum data rate requirement of each user, in which R_k is well discussed in Section II-C. Besides, $C2$ shows the non-negativity of the transmit power of each cluster. In addition, $C3$ demonstrates that each user can only be paired with one of the other user. Moreover, $C4$ represents that the user clustering index is a binary variable. Obviously, problem (9) is a hybrid integer nonlinear programming problem, which is in general difficult to solve [6]. In order to efficiently obtain the optimal solution, we propose a two-step methodology that decouples problem (9) into two subproblems, one is the user clustering and the other one is the power control for clusters.

III. User Clustering Algorithms and the Optimal Power Allocation Method

In this section, we first discuss the optimal and suboptimal user clustering schemes. Afterwards, we show that, given user pairing strategy, the resultant power control problem is standard and can be optimally solved via an iterative algorithm.

A. User Clustering Algorithms

1) Optimal User Clustering Method: The optimal user pairing can be obtained through an exhaustive search method. Since we have K users, the number of possible combinations for user clustering is

$$\Omega = (K-1)\times(K-3)\times\cdots\times 1. \tag{11}$$

Obviously, the computational complexity of the optimal user pairing method is too high to the practical system, especially, when the number of users is large. This motivates us to develop a suboptimal but efficient user clustering algorithm, which will be stated in next paragraph.

2) Suboptimal User Clustering Algorithm: The user pairing problem in cache based NOMA system is different from that in conventional NOMA due to the existing of cached information at users. Our suboptimal user clustering algorithm is designed based on two aspects: the different cached information at users[3] and the link gain differences among users. In detail, for any unpaired user i, we first search whether there exist some users j with $a_{i,j}=1$ and $a_{j,i}=1$. If so, user i will be paired to j who has the largest link gain difference from that of user i among the candidates. Otherwise, we will check whether there is a user j' that satisfies $g_i < g_{j'}$ and $j'\in\mathcal{S}_i$, which means user j' has a better channel condition than user i, and moreover, user i has packet $s_{j'}$ in its cache. If none of the above mentioned scenarios happens, we will pair user j'' who has the largest link gain difference from user i as the partner of user i. We summarize the pseudo-code of the proposed suboptimal user pairing method in Algorithm 1.

[3]The cached information at users affects cluster's power consumption. Detailed analysis is given in Section III-B1.

Algorithm 1 The suboptimal user clustering algorithm

Input: The link gain information g_k, where $k\in\mathcal{K}$ and the cache indicator vector $\boldsymbol{a}$. An auxiliary set $\mathcal{G}=\mathcal{K}$.
Output: $\mathcal{U}_n$ for $n\in\mathcal{N}$.

```
while G ≠ ∅ do
    if there exist some user j ∈ G \ {i} such that a_{i,j} = 1 and a_{j,i} = 1 then
        Let user j* = argmax_{a_{i,j}=1, a_{j,i}=1, j∈G\{i}} |g_i − g_j| be the partner of user i;
    else if there exist some user j > i and j ∈ S_i then
        Assign user j* = argmax_{j>i, j∈S_i, j∈G\{i}} |g_i − g_j| to the same cluster of user i.
    else
        Pair user j* = argmax_{j∈G\{i}} |g_i − g_j| to user i.
    end if
    G = G \ {i, j};
end while
return U_n for n ∈ N.
```

Proposition 2. *According to* (11)*, the computational complexity of the optimal user clustering is obtained as* $\mathcal{O}(K^{\frac{K}{2}-1})$*. Besides, based on Algorithm 1, the proposed suboptimal user pairing scheme has the complexity of* $\mathcal{O}(K^2/4)$.

B. Power Control with Given User Clustering

1) Minimum Required Power of Each Cluster: Given the user clustering results, and the transmit power of the other clusters, for $n\in\mathcal{N}$, the minimum required power of cluster n can be calculated directly based on the cached information at users. Details are given as follows:

Case 1: $a_{i,j}=0$, $a_{j,i}=0$ or $a_{i,j}=0$, $a_{j,i}=1$. In this case, the capacity of users i and j are given in Section II-C. The data rate constraints are listed below:

$$\hat{R}_i \geq \bar{R}_i,\ \text{and}\ \hat{R}_j \geq \bar{R}_j.$$

Obviously, the minimum total power required for cluster n is achieved when the above inequalities hold with strict equalities and it is then given by $\mathcal{F}_n=\gamma_i I_i+(1+\gamma_i)\gamma_j I_j$.

Case 2: $a_{i,j}=1$, $a_{j,i}=0$. Similarly, in this case, the minimum total power required is given by $\mathcal{F}_n=\gamma_j I_j+\max\{\gamma_i I_i, \gamma_i(1+\gamma_j)I_j\}$.

Case 3: $a_{i,j}=1$, $a_{j,i}=1$. Based on the proof of Theorem 1, the least needed power of this case is $\mathcal{F}_n=\max\{\gamma_i I_i,\gamma_j I_j\}$.

From above discussions, we draw up the conclusion that $P_n=\mathcal{F}_n(\boldsymbol{a},\boldsymbol{c},\boldsymbol{P}_{-n})$. Therefore, the original least data rate requirements for users can be transformed to the minimum power constraints of clusters, i.e.,

$$\begin{aligned} & P_n \geq \mathcal{F}_n(\boldsymbol{a},\boldsymbol{P}_{-n}),\ n\in\mathcal{N}\\ & P_n\geq 0 \end{aligned} \tag{12}$$

Note that, we ignored $\boldsymbol{c}$ in the expression of $\mathcal{F}_n$ due to the fact that the user clustering information is given.

2) Optimal Power Allocation Method: An iterative algorithm is designed in this paragraph to solve the above formulated power control problem. Let P_n^t be the transmit

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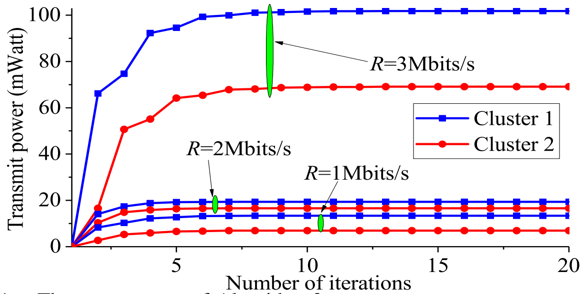

Fig. 1. The convergence of Algorithm 2

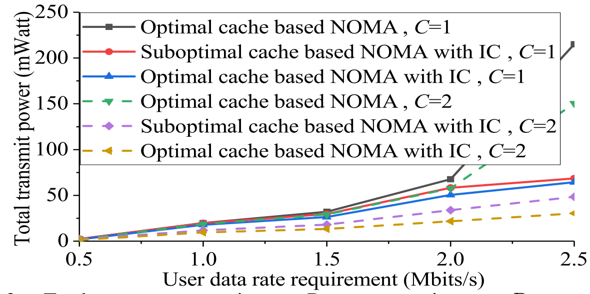

Fig. 2. Total power consumption v.s. Data rate requirement, R.

power of users in cluster n during the t^{th} iteration. Besides, let $\boldsymbol{P}_{-n}^t = (P_1^t, P_2^t, \ldots, P_{n-1}^t, P_{n+1}^t, \ldots, P_{|\mathcal{N}|}^t)$ and $\boldsymbol{P}^t = (P_1^t, P_2^t, \ldots, P_{|\mathcal{N}|}^t)$, respectively. The pseudo-code of the proposed power control method is stated in Algorithm 2, in which ε is a predefined value.

Algorithm 2 The iterative power allocation algorithm

1: Give a starting point $\boldsymbol{P}^0 = (0, 0, \ldots, 0)$, and $t = 1$.
2: **repeat**
3: **for** $n \in \mathcal{N}$ **do**
4: Calculate the required power of cluster n according to (12), i.e.,

$$P_n^t = \mathcal{F}_n(\boldsymbol{a}, \boldsymbol{P}_{-n}^{t-1}),\ n \in \mathcal{N}$$

5: **end for**
6: **until** $||\boldsymbol{P}^t - \boldsymbol{P}^{t-1}||_2^2 < \varepsilon$

In the following Theorem, we show that Algorithm 2 can achieve the optimal solution whenever the system is feasible.

Theorem 3. *Assuming that the system is feasible, the designed Algorithm 2 can converge to the optimal solution to the power control problem.*

Proof: Based on Algorithm 1, we can get the user pairing of all users, i.e., $\boldsymbol{c}$ is achieved. For cluster n, given $\boldsymbol{c}$ and the caching information $\boldsymbol{a}$, the needed minimum transmit power of cluster n to satisfy its associated users' data rate constraints can be obtained as a function of the required power of the other clusters $\boldsymbol{P}_{-n}$, which will be one of the three cases discussed in Section III-B1.

It is easy to check that the required power of the n^{th} cluster, $\mathcal{F}_n$, which can be regarded as the interference function of cluster n, satisfying the three criteria of standard [7]. According to Yate's power control framework [7], the iterative algorithm converges to the unique optimal solution given that the system is feasible. □

IV. Simulation Results

Monte-Carlo simulation is conducted to demonstrate the performance of our proposed joint user clustering and power control algorithm for cache-based NOMA system with mode selection. Random cache strategy is used in this work. The cell radius is 500 meters. A BS is located at the cell center and serves two clusters. The system bandwidth and the noise power spectral density are set to be 5 MHz and -174 dBm/Hz, respectively. For radio propagation model [8], the distance-dependent path loss is set to be $128.1 + 37.6 \log_{10} d$, where d is the distance between the BS and the receiver in kilometers, while for small-scale fading, we assume each user experiences independent Rayleigh fading with unit variance.

Fig. 1 shows the convergence performance of the proposed iterative power control algorithm. We use the transmit power of each cluster during the iterations to indicate the convergency. It can be seen that the iterative power allocation algorithm spends only several iterations to converge. Fig. 2 depicts the total power consumption versus different data rate requirements of users. For simplicity, we assume $\bar{R}_k = R$ for $k \in \mathcal{K}$. We randomly generate 100,000 instances and each point in Fig. 2 is obtained via averaging over all feasible instances. Obviously, with the increase of R, the total transmit power of all the three schemes increase. Besides, for any given R and C, both the optimal and the suboptimal cache based NOMA with IC outperform the optimal conventional cache based NOMA where pure SC is adopted. For example, with $R = 2.5$ Mbits/s and $C = 2$, our optimal and suboptimal cache based NOMA with IC saves power by 79.87% and 67.85% while comparing to the optimal conventional cache based NOMA. Moreover, the proposed suboptimal approach can reach a near optimal performance. Furthermore, the power consumptions of both two IC aided cache-based NOMA systems decrease as C increases.

V. Conclusion

We have looked into the possible benefits of the application of IC to cache based NOMA system in this letter. To solve the nonlinear hybrid integer programming problem, a two-step methodology was designed. In Step 1, we gave both the optimal and the suboptimal user clustering strategies. With the obtained user pairing results, the power control for all clusters are optimized in Step 2. Simulation results validated the convergence performance of the proposed power control method and shown the performance gains of our designed system in terms of power consumption compared to its conventional counterparts. This letter has provided a new horizon of thinking for cache-based NOMA networks and has emphasized that IC is more power efficient in certain caching scenario than SC. Future work includes the joint optimization of cache decision and resource management for NOMA networks.

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