

Harmonized Multiuser Transmission Scheme for Cellular Systems

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Abstract—Besides multiuser multi-input multi-output (MU-MIMO), non-orthogonal multiple access (NOMA) has been proposed as another promising alternative for multiuser multiplexing in cellular systems targeting for efficient spectrum utilization, and consequently has been attracting the attention of an increasing number of universities and institutes in both academic and industrial areas. In this paper, we focus on the azimuthal difference between the paired users, and investigate its influence on the system performance for both MU-MIMO and NOMA, respectively. The investigation reveals the different preference of the both schemes in respect of the inter-user azimuthal difference. Accordingly, a harmonized transmission framework for multiuser multiplexing has been proposed whereby the better transmission scheme of the both is always selected. Theoretical analysis justifies its effectiveness.

Index Terms—Azimuthal difference, deviation, multiuser multiplexing, MU-MIMO, NOMA.

I. INTRODUCTION

Over the last decade, with the new service types emerging and wireless traffic soaring, high speed data rate access is becoming increasingly necessary and important. To this end, spectral efficiency needs to be improved further or wider spectrum should be used. However, radio spectrum has always been the most valuable and scarcest resource in wireless communication. Besides the exploration of wider and higher frequency bands, one of the biggest challenges is how to utilize the existing spectrum in an extremely efficient way.

In a cellular system, a base station (BS) needs to provide service to its associated users. Clearly, scheduling multiple users in a frequency division multiplexing (FDM) or time division multiplexing (TDM) manner cannot contribute to spectral efficiency enhancement. Instead, a BS can only resort to the technologies whereby multiple users can be scheduled for co-transmission on the same frequency resource simultaneously. Regarding the technologies, multiuser multi-input multi-output (MU-MIMO) [1]–[3] and *non-orthogonal multiple access (NOMA)* [4]–[6] are two typical candidates.

MU-MIMO transmission is widely used in cellular systems to deal with the restriction of the conventional single user MIMO (SU-MIMO) scheme that the link capacity is constrained to the number of the antennas equipped at one user. In MU-MIMO, the antennas of the co-scheduled users, probably geographically separated, can be equivalently treated as one virtual antenna array. Therefore, MU-MIMO is also termed *virtual MIMO*. Since it was proposed, a variety of MU-MIMO specific beamforming schemes have emerged, e.g.

zero forcing (ZF), block diagonalization (BD), and etc. What is interesting, in the presence of a large number of candidate users, remarkable *multiuser diversity gain* can be obtained due to the opportunistic user scheduling and pairing. Moreover, a carefully dedicated ZF-based beamforming scheme can be asymptotically optimal and the achievable throughput can approach that of *dirty paper coding (DPC)* [1], [7], i.e. the theoretical upper bound of MIMO broadcast channels [8]. Hence, the capacity of cellular systems can be significantly enhanced by the technology.

The concept of NOMA was proposed as a new multiple access strategy towards future wireless systems, and is completely different from the orthogonal manner adopted in existing systems. According to the knowledge in information theory, NOMA has a larger capacity region than orthogonal multiple access (OMA) schemes. Therefore, it has already given rise to a series of research activities in the industry, e.g. a new study item termed “study on downlink multiuser superposition transmission for LTE” was approved by 3rd generation partnership project (3GPP) in March, 2015 [9], and further it has already been identified as one of the most remarkable features of long term evolution advanced professional (LTE-AdvancedPro) release 13.

In essence, both MU-MIMO and NOMA are multiuser multiplexing methods or equivalently multiple access schemes without time domain or frequency domain separation. Literally, the former multiplexes users in spatial domain, while the latter performs multiplexing in one or more non-orthogonal dimensions, e.g. power dimension. Obviously, NOMA has a very large scope. Moreover, in strict sense, MU-MIMO is also a kind of NOMA, since the spatial domain is not a fully orthogonal dimension due to the existence of inter-user interference. But in this paper, as in the majority of the existing literatures, NOMA means the power domain multiplexing with no separation but complete superposition in spatial domain.

In this paper, we focus on the azimuthal difference between the co-scheduled users, and investigate its influence on the system performance for both MU-MIMO and NOMA, respectively. In the light of the investigation, the both schemes have different preference in respect of the inter-user azimuthal difference. Targetting for better performance, a harmonized and unified framework for multiuser multiplexing and transmission has been proposed whereby the better transmission scheme of the both is always selected. In other words, a feasible criteria for dynamic switching between MU-MIMO and NOMA is

proposed. Its effectiveness is justified by theoretical analysis.

The remainder of this paper is structured as follows. The system model is briefly introduced in Section II. In Section III, the proposed scheme is presented in detail. Finally, conclusions are drawn in Section IV.

Throughout this paper, we adopt the following notational convention: Scalars are denoted by upper-case or lower-case plain letters, and their absolute values can be obtained by $|\cdot|$. Vectors and matrices are expressed by lower-case boldface and upper-case boldface letters, respectively. $\|\cdot\|_F^2$ returns their Frobenius norms. $\mathbb{C}^{m \times n}$ stands for the complex matrix space of dimension $m \times n$. Particularly, $\mathbb{C}^{m \times 1}$ and $\mathbb{C}^{1 \times n}$ denote the complex column and row vector spaces of dimension m and n , respectively. $\mathcal{CN}(0, \sigma^2)$ represents the zero mean circularly symmetric complex Gaussian (ZMCSCG) distribution with variance σ^2 . $\mathcal{E}(\cdot)$ is the expectation operator for random variables.

II. SYSTEM MODEL

Without loss of generality, we consider a simple scenario that a BS equipped with N antennas selects a couple of single antenna users, user-1 and user-2, for NOMA or MU-MIMO transmission. A birdview of the system model can be illustrated in Fig. 1. For user- i , x_i is its constellation symbol with a unit power, i.e. $\mathcal{E}(|x_i|^2) = 1$; its polar coordinate is denoted by (r_i, θ_i) ; the downlink channel from the BS can be characterized by a large scale distance-dependent fading $L(r_i)$ and a small scale fading $\mathbf{h}_i \in \mathbb{C}^{1 \times N}$; $i = 1, 2$. The total power constraint at the BS is P_t , a fraction α of which is allocated to user-1 and the rest $1 - \alpha$ of which is assigned to user-2, $\alpha \in [0, 1]$.

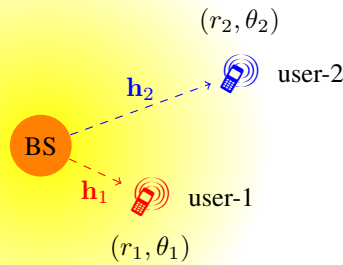


Fig. 1. System model

A. NOMA

Generally speaking, for NOMA transmission, the channel state information (CSI) of the paired users, e.g. user-1 and user-2, should meet two requirements: approximate or the same precoding matrix index (PMI) and different enough channel quality indicator (CQI). The former guarantees the

azimuthal concentration of the co-scheduled users for large beamforming gain and high power efficiency; while the latter utilizes large propagation difference for easy distinction and separation in power dimension. Accordingly, a BS allocates a majority of its power to the *far user* (e.g. user-2) to conquer the severe path loss, and assign less power to the *near user* (e.g. user-1). The received signals at user-1 and user-2 can be written as

$$y_1 = \sqrt{P_t L(r_1)} \mathbf{h}_1 \mathbf{w} (\sqrt{\alpha} x_1 + \sqrt{1 - \alpha} x_2) + n_1, \quad (1)$$

$$y_2 = \sqrt{P_t L(r_2)} \mathbf{h}_2 \mathbf{w} (\sqrt{\alpha} x_1 + \sqrt{1 - \alpha} x_2) + n_2, \quad (2)$$

where $\mathbf{w} \in \mathbb{C}^{N \times 1}$ is the power normalized beamforming vector shared by the both users, $\|\mathbf{w}\|_F^2 = 1$; n_i is the additive Gaussian noise at the user- i , $n_i \sim \mathcal{CN}(0, \sigma_i^2)$, $i = 1, 2$.

In this case, after experiencing the serious attenuation, the interference user-2 suffers from user-1 becomes very weak and tolerable. Thus, the user-2 can still detect its own data successfully. However, this is not the case for user-1. In the presence of the strong interference, i.e. the data intended for user-2, user-1 has to first detect and cancel the interference before obtaining its own data. To this end, the BS usually needs to signal user-1 the necessary configurations and parameters of the transmission to user-2. With the information available, the interference user-1 suffers can be cancelled precisely. Owing to the smaller propagation attenuation, even though less power is allocated to it, user-1 is still able to detect its own data correctly.

B. MU-MIMO

For MU-MIMO transmission, what is different from NOMA, two different beamforming vectors can be adopted for the two users. Accordingly, the received signals at the both users can be expressed as

$$\begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = \sqrt{P_t} \begin{bmatrix} \mathbf{h}_1 \\ \mathbf{h}_2 \end{bmatrix} \begin{bmatrix} \mathbf{w}_1 & \mathbf{w}_2 \end{bmatrix} \begin{bmatrix} \sqrt{\alpha} x_1 \\ \sqrt{1 - \alpha} x_2 \end{bmatrix} + \begin{bmatrix} n_1 \\ n_2 \end{bmatrix}, \quad (3)$$

where $\mathbf{w}_i \in \mathbb{C}^{N \times 1}$ is the power normalized beamforming vector for user- i , $\|\mathbf{w}_i\|_F^2 = 1$, $i = 1, 2$.

III. PROPOSED SCHEME

In this section, the influence of the azimuthal difference on the system performance is first investigated for both NOMA and MU-MIMO, respectively. Then, the proposed scheme is presented in detail.

A. NOMA

From its principle, we understand that NOMA transmission favors user pairs with very similar, ideally the same azimuths, i.e. $\theta_1 \approx \theta_2$. In this case, the BS can concentrate its power on the azimuth of the user pair. Considerable beamforming gain and excellent performance can be obtained. On the contrary, if the inter-user azimuthal difference, e.g. $|\theta_1 - \theta_2|$, is large, no matter how the BS tunes its beam, at least one user suffers reduced beamforming gain. If the BS steers its beam towards one user, then the other user will suffer degraded beamforming

performance. Therefore, the performance of NOMA transmission is very sensitive to the inter-user azimuthal difference.

According to (1) and (2), the signal-to-interference-plus-noise-power-ratios (SINR's) of the both users can be obtained as

$$\begin{aligned}\Gamma_1^{\text{NOMA}}(\mathbf{w}) &= \frac{\alpha P_t L(r_1) |\mathbf{h}_1 \mathbf{w}|^2}{\sigma_1^2} \\ &= \alpha \gamma_1 |\mathbf{h}_1 \mathbf{w}|^2\end{aligned}\quad (4)$$

$$\begin{aligned}\Gamma_2^{\text{NOMA}}(\mathbf{w}) &= \frac{(1-\alpha) P_t L(r_2) |\mathbf{h}_2 \mathbf{w}|^2}{\alpha P_t L(r_2) |\mathbf{h}_2 \mathbf{w}|^2 + \sigma_2^2} \\ &= \frac{(1-\alpha) |\mathbf{h}_2 \mathbf{w}|^2}{\alpha |\mathbf{h}_2 \mathbf{w}|^2 + \frac{1}{\gamma_2}},\end{aligned}\quad (5)$$

where $\gamma_i = \frac{P_t L(r_i)}{\sigma_i^2}$ is the geometry SINR of user- i , which can be measured based on the downlink pilots or reference signals, $i = 1, 2$.

For clear description, we use a function $g(\xi)$ to quantitatively characterize the extent to which the beamforming vector $\mathbf{w}$ matches the channel to a user, where ξ is the azimuthal deviation of the user from the beam axis. Then, we have

$$\begin{aligned}|\mathbf{h}_1 \mathbf{w}|^2 &= A(\theta_1) g(\phi - \theta_1) \\ |\mathbf{h}_2 \mathbf{w}|^2 &= A(\theta_2) g(\phi - \theta_2),\end{aligned}$$

where $A(\cdot)$ is the pattern of each antenna and ϕ is the azimuth of the formed beam, which corresponds to beamforming vector $\mathbf{w}$ and varies between θ_1 and θ_2 . Accordingly, the SINR's of the both users can be rewritten as

$$\Gamma_1^{\text{NOMA}}(\phi) = \alpha \gamma_1 A(\theta_1) g(\phi - \theta_1) \quad (6)$$

$$\Gamma_2^{\text{NOMA}}(\phi) = \frac{(1-\alpha) A(\theta_2) g(\phi - \theta_2)}{\alpha A(\theta_2) g(\phi - \theta_2) + \frac{1}{\gamma_2}}. \quad (7)$$

Specially, if the BS steers its beam towards user-1, i.e. $\phi = \theta_1$, the SINR's of the both users become

$$\begin{aligned}\Gamma_1^{\text{NOMA}}(\theta_1) &= \alpha \gamma_1 A(\theta_1) g(0) \\ \Gamma_2^{\text{NOMA}}(\theta_1) &= \frac{(1-\alpha) A(\theta_2) g(\delta_{1,2})}{\alpha A(\theta_2) g(\delta_{1,2}) + \frac{1}{\gamma_2}},\end{aligned}$$

where $\delta_{1,2} = |\theta_1 - \theta_2|$ is the azimuthal difference between the both users. If the BS tunes its beam pointing to user-2, i.e. $\phi = \theta_2$, their SINR's turn to be

$$\begin{aligned}\Gamma_1^{\text{NOMA}}(\theta_2) &= \alpha \gamma_1 A(\theta_1) g(\delta_{1,2}) \\ \Gamma_2^{\text{NOMA}}(\theta_2) &= \frac{(1-\alpha) A(\theta_2) g(0)}{\alpha A(\theta_2) g(0) + \frac{1}{\gamma_2}}.\end{aligned}$$

As a compromise, the BS can adjust its beam to the middle of the azimuths of the both users, i.e. $\phi = \frac{\theta_1 + \theta_2}{2}$. In this case, their SINR's can be given by

$$\begin{aligned}\Gamma_1^{\text{NOMA}}\left(\frac{\theta_1 + \theta_2}{2}\right) &= \alpha \gamma_1 A(\theta_1) g\left(\frac{\delta_{1,2}}{2}\right) \\ \Gamma_2^{\text{NOMA}}\left(\frac{\theta_1 + \theta_2}{2}\right) &= \frac{(1-\alpha) A(\theta_2) g\left(\frac{\delta_{1,2}}{2}\right)}{\alpha A(\theta_2) g\left(\frac{\delta_{1,2}}{2}\right) + \frac{1}{\gamma_2}}.\end{aligned}$$

B. MU-MIMO

Similarly, according to (3), the SINR's of the both users can be calculated by

$$\begin{aligned}\Gamma_1^{\text{MU-MIMO}}(\phi_1, \phi_2) &= \frac{\alpha P_t L(r_1) |\mathbf{h}_1 \mathbf{w}_1|^2}{(1-\alpha) P_t L(r_1) |\mathbf{h}_1 \mathbf{w}_2|^2 + \sigma_1^2} \\ &= \frac{\alpha A(\theta_1) g(\phi_1 - \theta_1)}{(1-\alpha) A(\theta_1) g(\phi_2 - \theta_1) + \frac{1}{\gamma_1}}\end{aligned}\quad (8)$$

$$\begin{aligned}\Gamma_2^{\text{MU-MIMO}}(\phi_1, \phi_2) &= \frac{(1-\alpha) P_t L(r_2) |\mathbf{h}_2 \mathbf{w}_2|^2}{\alpha P_t L(r_2) |\mathbf{h}_2 \mathbf{w}_1|^2 + \sigma_2^2} \\ &= \frac{(1-\alpha) A(\theta_2) g(\phi_2 - \theta_2)}{\alpha A(\theta_2) g(\phi_1 - \theta_2) + \frac{1}{\gamma_2}},\end{aligned}\quad (9)$$

where ϕ_i is the azimuth of the beam dedicated for user- i , corresponding to beamforming vector $\mathbf{w}_i$, $i = 1, 2$.

Taking the popular ZF-based scheme for instance, the inter-user interference can be completely mitigated by zero-forcing projection. Alternatively, it can be realized by $\phi_1 = \theta_2 - \theta_{\text{null}}$, $\phi_2 = \theta_1 + \theta_{\text{null}}$, where θ_{null} is a *null azimuth*, i.e. $g(\theta_{\text{null}}) = 0$, which is an inherent attribute of the antenna array at the BS. The SINR's of the both users in (8) and (9) can be further simplified as

$$\Gamma_1^{\text{ZF-MU-MIMO}}(\delta_{1,2}) = \alpha \gamma_1 A(\theta_1) g(\theta_{\text{null}} - \delta_{1,2}) \quad (10)$$

$$\Gamma_2^{\text{ZF-MU-MIMO}}(\delta_{1,2}) = (1-\alpha) \gamma_2 A(\theta_2) g(\theta_{\text{null}} - \delta_{1,2}). \quad (11)$$

C. Proposed scheme

Based on the SINR's of the both users in (6), (7), (10) and (11), the SINR region of the both users can be shown in Fig. 2.

Given an inter-user azimuthal difference $\delta_{1,2}$, the achievable SINR performance of the NOMA scheme varies as the beam azimuth goes from the azimuth of user-1 ($\phi = \theta_1$) to that of user-2 ($\phi = \theta_2$). As expected, when $\phi = \theta_1$, user-1 can obtain the maximal beamforming gain, while user-2 suffers the minimal beamforming gain; when $\phi = \theta_2$, user-2 can enjoy the largest beamforming gain, while user-1 suffers the most severe loss due to the large azimuthal deviation from the beam axis. In other words, there is always a tradeoff between the beamforming gains of the both users.

However, this is not the case for the ZF-based MU-MIMO case. Instead, the SINR's of the two users fully depend on the azimuthal difference between the both users $\delta_{1,2}$ and the null

azimuth θ_{null} . As illustrated in Fig. 2, the SINR performance can be represented by a cluster of parallel lines. Particularly, in the case of $\delta_{1,2} = \theta_{\text{null}}$, when the BS steers a beam to one user, fortunately there is completely no interference leaked to the other user, and it outperforms the NOMA scheme. If $\delta_{1,2} = \theta_{\text{null}}/2$, remarkable beamforming gain is sacrificed in the zero forcing processing, and ZF-based scheme performs worse than the NOMA scheme.

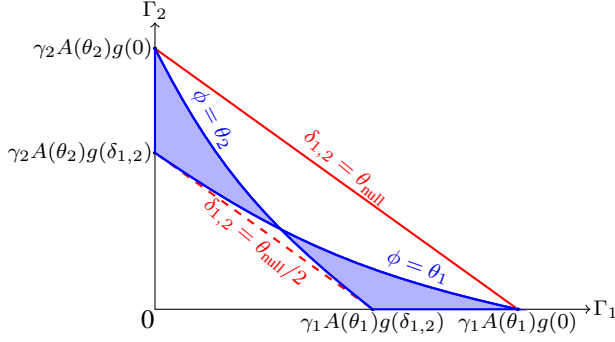


Fig. 2. Achievable SINR region of user-1 and user-2.

In a word, irrespective of NOMA or MU-MIMO, the most decisive factor is the azimuthal difference between the paired users¹. In the light of the different preference of the both schemes in respect of the inter-user azimuthal difference, a harmonized multiuser transmission scheme can be proposed, whereby transmission mode can be flexibly switched between NOMA and MU-MIMO. Given a pair of users, e.g. user- i and user- j , the favorable multiuser transmission mode for them can be determined as follows.

- 1) Compute the azimuthal difference between user- i and user- j , $\delta_{i,j}$.
- 2) Compare $\delta_{i,j}$ with the null azimuth of the antenna array at the BS, θ_{null} .
 - If $\delta_{i,j} \leq \theta_{\text{null}}/2$, adopt NOMA scheme. In this case, the paired users cannot be well separated in spatial domain, and this will definitely degrade the performance of MU-MIMO. But the azimuthal concentration is preferred by NOMA scheme.
 - If $\delta_{i,j} \geq \theta_{\text{null}}$, use MU-MIMO scheme. In this case, good separation in the spatial domain yields negligible inter-user interference. Hence, compared to NOMA, MU-MIMO can provide better performance.
 - If $\theta_{\text{null}}/2 < \delta_{i,j} < \theta_{\text{null}}$, evaluate the achievable performance metrics of both NOMA and MU-MIMO and thereby make the final decision for transmission mode. The performance metric can be weighted sum of SINR or throughput of the co-scheduled users². Essentially, this case corresponds to the

¹The CQI gap between the paired users is assumed to be sufficiently large for NOMA transmission herein.

²In fact, for the popular proportional fairness (PF) scheduling, the performance metric is a weighted sum of user's throughput.

region between the two red parallel lines (a solid and a dashed) in Fig. 2, and the SINR curves of the both schemes have intersection points. Which scheme is better depends on the target performance metric. Thus, it is indispensable for the BS to compare the achievable performance of the both schemes.

Clearly, the proposed scheme provides a feasible criteria for dynamic switching between NOMA and MU-MIMO, whereby for each potential user pair, a better choice can always be guaranteed. Consequently, it can provide a better performance than either the pure NOMA or the pure MU-MIMO schemes.

IV. CONCLUSIONS

In this paper, from the perspective of azimuthal difference between the co-scheduled users, the performance of NOMA and MU-MIMO were investigated in detail. Moreover, based on the different preference of the both schemes in respect of the inter-user azimuthal difference, a harmonized multiuser multiplexing framework was proposed. In other words, a feasible criteria for dynamic switching between NOMA and MU-MIMO was provided. Its effectiveness was verified by theoretical analysis.

Moreover, it should be noticed that even though the beamforming was restricted only in azimuthal dimension in this paper, it can be directly extended to the elevation domain, especially when 2-dimension antenna arrays are equipped at BS's, i.e. full-dimension MIMO (FD-MIMO) or 3-dimension MIMO (3D-MIMO) systems. Additionally, more general MU-MIMO schemes beyond ZF will be explored in the future work.

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