Non-Orthogonal Multiple Access in Downlink Coordinated Two-Point Systems

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***Abstract*—In order to improve the spectral efficiency, non-orthogonal multiple access (NOMA) with superposition coding is employed in a coordinated system where downlink signals to users near to base stations (BSs) and cell-edge users are transmitted simultaneously. To support a cell-edge user in a NOMA channel, two coordinated BSs use Alamouti code. In order to see the performance, we derive expressions for the transmission rates to near and cell-edge users. It is shown that the proposed coordinated superposition coding (CSC) scheme can provide a reasonable transmission rate to a cell-edge user without degrading the rates to users near to BSs.**

***Index Terms*—Coordinated multipoint (CoMP), superposition coding, interference cancellation.**

I. Introduction

IN cellular systems, the transmission rate to a cell-edge user is lower than that to a user near to a base stations (BS) due to propagation losses. To increase transmission rates to cell-edge users, coordinated multipoint (CoMP) transmission (and reception) techniques are studied where multiple BSs support cell-edge users together [1], [2]. For downlink CoMP, various schemes can be considered from dynamic cell selection (DCS) to coordinated beamforming [3], [4] if instantaneous channel state information (CSI) is available at BSs.

For CoMP transmissions in downlink, all associated BSs for CoMP need to allocate the same channel to a cell-edge user and this channel cannot be allocated to other users simultaneously if orthogonal multiple access is employed. Thus, as the number of cell-edge users increases, the spectral efficiency of the system becomes worse. To avoid this problem, non-orthogonal multiple access (NOMA) [5] can be employed.

In this paper, we consider superposition coding (SC) [6], which is a well-known non-orthogonal scheme, for downlink transmissions to a group of cell-edge user and user near to a BS simultaneously with a common access channel [7]. For a cell-edge user, the Alamouti code [8] is employed at two BSs for CoMP transmissions as it does not require any instantaneous CSI exchange, which is an important advantage over coherent transmission schemes that require instantaneous CSI exchange, which results in an excessive backhaul overhead for cell-edge users of high mobility.

Notation: The superscripts T and H denote the transpose and Hermitian transpose, respectively. The superscript $*$ stands for the complex conjugate. $\mathbb{E}[\cdot]$ denotes the expectation. $\mathcal{CN}(\mathbf{a}, \mathbf{R})$ represents the distribution of circularly-symmetric complex Gaussian (CSCG) random vectors with mean vector $\mathbf{a}$ and covariance matrix $\mathbf{R}$.

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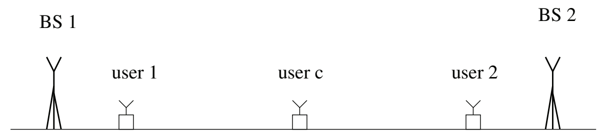

Fig. 1. An illustration of a CoMP system with two BSs.

II. NOMA with Alamouti Code

In this section, we consider coordinated SC (CSC) to support a cell-edge user using the Alamouti code [8]. In particular, as shown in Fig. 1, two BSs transmit Alamouti (space-time) coded signals to user c (a cell-edge user), while each BS also transmits signals to a user near to the BS (this user will be referred to as a near user). In [9], a similar approach is considered with beamforming to mitigate interfering signals. On the other hand, since we assume that each BS has a single transmit antenna, no beamforming is considered in this paper.

Let $h_{i,j}$, $i \in \{1, 2, \mathrm{c}\}, j \in \{1, 2\}$, denote the channel coefficient from BS j to user i. Denote by $s_i(t)$, $i = 1, 2$, the data symbol to user i from BS i at time t. Both BSs also transmit Alamouti coded signals to the cell-edge user, user c, using SC. Let $a(1)$ and $-a^*(2)$ be the data symbols to be transmitted over the first and second time slots, respectively, from BS 1. Then, BS 2 transmits $a(2)$ and $a^*(1)$ over the first and second time slots, respectively. For notational convenience, let $s_\mathrm{c}(t)$ and $\bar{s}_\mathrm{c}(t)$ denote the data symbols to user c from BSs 1 and 2, respectively. That is, during the first (resp., second) time slot, $s_\mathrm{c}(1) = a(1)$ (resp., $s_\mathrm{c}(2) = -a^*(2)$) and $\bar{s}_\mathrm{c}(1) = a(2)$ (resp., $\bar{s}_\mathrm{c}(2) = a^*(1)$) are the signals to be transmitted by BSs 1 and 2 to user c, respectively. The time index, t, would be omitted in this section, if there is no risk of confusion. Then, the received signals at the three users are

$$\begin{aligned} r_1 &= h_{1,1}(s_1 + s_\mathrm{c}) + h_{1,2}(s_2 + \bar{s}_\mathrm{c}) + n_1; \\ r_2 &= h_{2,2}(s_2 + \bar{s}_\mathrm{c}) + h_{2,1}(s_1 + s_\mathrm{c}) + n_2; \\ r_\mathrm{c} &= h_{\mathrm{c},1}(s_1 + s_\mathrm{c}) + h_{\mathrm{c},2}(s_2 + \bar{s}_\mathrm{c}) + n_\mathrm{c}, \end{aligned} \quad (1)$$

where r_i and n_i are the received signal and noise at user i, $i \in \{1, 2, \mathrm{c}\}$, respectively. Let $P_i = \mathbb{E}[|s_i|^2]$, $i \in \{1, 2\}$. As the powers of s_c and $\bar{s}_\mathrm{c}$ are the same due to the Alamouti code, let $P_\mathrm{c} = \mathbb{E}[|s_\mathrm{c}|^2] + \mathbb{E}[|\bar{s}_\mathrm{c}|^2] = 2\mathbb{E}[|s_\mathrm{c}|^2]$. P_1 and P_2 would be much lower than P_c.

At user 1, if the Alamouti coded signals, s_c and $\bar{s}_\mathrm{c}$, to user c are decodable[1] and successive interference cancelation (SIC)

[1]We need two time slots for decoding as s_c and $\bar{s}_\mathrm{c}$ are Alamouti coded signals.

is applied, we have

$$r_1 - (h_{1,1}s_c + h_{1,2}\bar{s}_c) = h_{1,1}s_1 + h_{1,2}s_2 + n_1. \quad (2)$$

Since the powers of s_1 and s_2 are similar and $h_{1,2}$ is much weaker than $h_{1,1}$, s_2 is not decodable. Thus, the rate to user 1 would be decided with the interfering signal, s_2, as in (2). A similar method can be used to decide the rate to user 2.

At user c, the interfering signals, s_1 and s_2, may not be decodable as P_1 and P_2 are lower than P_c. Thus, in r_c, $h_{c,1}s_1$ and $h_{c,2}s_2$ would be considered as the background noise.

For comparison purposes, we also consider another NOMA scheme where only one BS, say BS 1, employs SC to support a pair of cell-edge and near users simultaneously. The resulting received signals at the three users are as follows:

$$\begin{aligned} r_1 &= h_{1,1}(s_1 + s_c) + h_{1,2}s_2 + n_1; \\ r_2 &= h_{2,2}s_2 + h_{2,1}(s_1 + s_c) + n_2; \\ r_c &= h_{c,1}(s_1 + s_c) + h_{c,2}s_2 + n_c, \end{aligned} \quad (3)$$

which are the same as those in (1) except that $\bar{s}_c = 0$ and $\mathbb{E}[|s_c|^2] = P_c$ (as only one BS transmits signals to user c). At user 2, since $h_{2,1}$ is weaker than $h_{2,2}$, s_c may not be decodable. Thus, in this case, we assume that SIC is applied only to user 1. The system corresponding to (1) is referred to as the CSC system, while that corresponding to (3) is referred to as the non-CSC system. Note that in the non-CSC system, the best[2] BS can be chosen to support user c, which is DCS [2]. The resulting system is referred to as the DCS-SC system. Clearly, DSC-SC differs from CSC and non-CSC in the sense that it requires instantaneous CSI to user c at BSs.

III. Performance Analysis

For tractable analysis to see the impact of NOMA with SC on the performances of CSC, non-CSC, and DSC-SC, we consider the following assumption in this section:

A1) $P_1 = P_2 = P$ and $\sigma_1^2 = \sigma_2^2 = \sigma_c^2 = \sigma^2$.

Throughout the paper, we also assume that $s_1(t)$, $s_2(t)$, and $a(t)$ are independently coded signals with Gaussian codebooks and the maximum likelihood (ML) decoding is employed at all the receivers with known CSI in order to achieve the Shannon capacity.

A. CSC System

We mainly consider the receiver at user 1, where the signal to user c is decoded first for SIC, and then s_1 is decoded. With two consecutive received signals, $r_1(t)$, $t = 1, 2$, define $[y_1(1)\ y_1(2)]^{\mathrm{T}} = \mathbf{H}_1^{\mathrm{H}}[r_1(1)\ r_1(2)]^{\mathrm{T}}$, where $\mathbf{H}_1 = \begin{bmatrix} h_{1,1} & h_{1,2} \\ h_{1,2}^* & -h_{1,1}^* \end{bmatrix}$, which is given by

$$\begin{aligned} y_1(1) &= (|h_{1,1}|^2 + |h_{1,2}|^2)a(1) \\ &\quad + |h_{1,1}|^2 s_1(1) + h_{1,1}^* h_{1,2} s_2(1) \\ &\quad + h_{1,1}^* h_{1,2} s_1(2) + |h_{1,2}|^2 s_2(2) + \tilde{n}_1(1); \\ y_1(2) &= (|h_{1,1}|^2 + |h_{1,2}|^2)a(2) \\ &\quad + |h_{1,2}|^2 s_2(1) + h_{1,1} h_{1,2}^* s_1(1) \\ &\quad - |h_{1,1}|^2 s_1(2) - h_{1,1} h_{1,2}^* s_2(2) + \tilde{n}_1(2), \end{aligned} \quad (4)$$

where $\tilde{n}_1(t) \sim \mathcal{CN}(0, (|h_{1,1}|^2 + |h_{1,2}|^2)\sigma^2)$, $t = 1, 2$. After some manipulations, the SINR becomes

$$\mathsf{SINR}_1 = \frac{(|h_{1,1}|^2 + |h_{1,2}|^2)\frac{P_c}{2}}{(|h_{1,1}|^2 + |h_{1,2}|^2)P + \sigma^2}. \quad (5)$$

The corresponding rate is $Z_1 = \mathbb{E}[\log_2(1 + \mathsf{SINR}_1)]$. Using a similar approach, at user 2, the SINR in decoding s_c can be found as

$$\mathsf{SINR}_2 = \frac{(|h_{2,2}|^2 + |h_{2,1}|^2)\frac{P_c}{2}}{(|h_{2,2}|^2 + |h_{2,1}|^2)P + \sigma^2}, \quad (6)$$

and $Z_2 = \mathbb{E}[\log_2(1 + \mathsf{SINR}_2)]$.

After SIC, the rate to user 1 can be found from (2), where $h_{1,2}s_2 + n_1$, which is independent of $h_{1,1}s_1$, is considered as the background noise. Thus, the rates to users 1 and 2 are given by $R_1 = \mathbb{E}\left[\log_2\left(1 + \frac{|h_{1,1}|^2 P_1}{\mathbb{E}[|h_{1,2}|^2]P_2 + \sigma_1^2}\right)\right]$ and $R_2 = \mathbb{E}\left[\log_2\left(1 + \frac{|h_{2,2}|^2 P_2}{\mathbb{E}[|h_{2,1}|^2]P_1 + \sigma_2^2}\right)\right]$, respectively.

At user c, using two time slots, the desired signal, s_c, is to be decoded. Using the approach in above, the SINR at user c becomes

$$\mathsf{SINR}_c = \frac{(|h_{c,1}|^2 + |h_{c,2}|^2)\frac{P_c}{2}}{(|h_{c,1}|^2 + |h_{c,2}|^2)P + \sigma^2}. \quad (7)$$

The corresponding rate is $Z_c = \mathbb{E}[\log_2(1 + \mathsf{SINR}_c)]$. Since s_c has to be decoded at users 1 and 2 for SIC, the maximum transmission rate of s_c has to be upper-bounded as

$$R_{ex} = \min\{Z_1, Z_2, Z_c\}, \quad (8)$$

which is the extra rate using CSC to support a cell-edge user.

For convenience, define $C(X) = \log_2(1 + X)$, where X is a non-negative random variable and let $\gamma = \frac{P}{\sigma^2}$ and $\gamma_c = \frac{P_c}{\sigma^2}$. Then, we can show that

$$\begin{aligned} Z_i &= \mathbb{E}\left[C\left((|h_{i,1}|^2 + |h_{i,2}|^2)\left(\frac{\gamma_c}{2} + \gamma\right)\right)\right] \\ &\quad - \mathbb{E}\left[C\left((|h_{i,1}|^2 + |h_{i,2}|^2)\gamma\right)\right], \ i \in \{1, 2, c\}. \end{aligned} \quad (9)$$

We assume the following symmetric channel conditions:

A2) Let $h_{i,j} \sim \mathcal{CN}(0, P_0 d_{i,j}^{-\eta})$, where P_0 is a normalization constant, $d_{i,j}$ is the distance between user i and BS j, and η denotes the path loss exponent. For each (i, j), assume that $\mathbb{E}[|h_{1,1}|^2] = \mathbb{E}[|h_{2,2}|^2] = \psi$, $\mathbb{E}[|h_{2,1}|^2] = \mathbb{E}[|h_{1,2}|^2] = \beta$, and $\mathbb{E}[|h_{c,1}|^2] = \mathbb{E}[|h_{c,2}|^2] = \alpha$, where

$$\psi > \alpha > \beta > 0. \quad (10)$$

Under **A2)**, to find expressions for Z_i in (9), we need the ergodic capacity expression for unequal branch gains or correlated gains that is derived in [10]. In App. A, we derive it again in a slightly different way to obtain few useful properties.

For convenience, let $C_t(x)$ denote the ergodic capacity with t-fold MRC of equal gains, which is given by [11]

$$\mathcal{C}_t(x) = \frac{e^{\frac{1}{x}}}{\ln 2} \sum_{k=0}^{t-1} E_{k+1}\left(\frac{1}{x}\right), \quad (11)$$

where $E_n(x) = \int_1^\infty \frac{e^{-xt}}{t^n} dt$. Under **A2)**, from App. A, we have

$$\begin{aligned} Z_1 &= Z_2 \\ &= \frac{\psi(\mathcal{C}_1(\psi\gamma_A) - \mathcal{C}_1(\psi\gamma)) - \beta(\mathcal{C}_1(\beta\gamma_A) - \mathcal{C}_1(\beta\gamma))}{\psi - \beta}, \end{aligned} \quad (12)$$

[2]The best BS can be decided by the channel gains. For example, BS 1 is chosen if $|h_{c,1}|^2 > |h_{c,2}|^2$. Otherwise, BS 2 is chosen. This decision can be made at user c and sent back to BSs.

where $\gamma_A = \frac{\gamma_c}{2} + \gamma$. Furthermore, we have

$$Z_c = \mathcal{C}_2(\alpha\gamma_A) - \mathcal{C}_2(\alpha\gamma). \quad (13)$$

Under **A2)**, it can be shown that $R_1 = R_2 = \mathcal{C}_1\left(\frac{\psi\gamma}{\beta\gamma+1}\right)$. The sum rate becomes $R_1 + R_2 + R_{ex}$.

Using (21) in App. A, it can be shown that Z_1 converges to Z_c if $\psi, \beta \to \alpha$, which would be the case where both near users approach user c. This leads to $R_{ex} \to Z_c$.

B. Non-CSC and DSC-SC Systems

In this subsection, we derive the transmission rates to users i in the non-CSC and DSC-SC systems under **A2)** using the results in App. A.

Denote by $\tilde{R}_i$ the rates to user i, $i \in \{1, 2\}$ in the non-CSC system. Since SIC is applied to user 1 only, under **A1)**, the rates to users 1 and 2 can be found as

$$\begin{aligned}\tilde{R}_1 &= R_1;\\ \tilde{R}_2 &= \mathbb{E}\left[\log_2\left(1 + \frac{|h_{2,2}|^2\gamma}{\mathbb{E}[|h_{2,1}|^2](\gamma_c+\gamma)+1}\right)\right]\\ &= \mathcal{C}_1\left(\frac{\psi\gamma}{\beta(\gamma_c+\gamma)+1}\right). \quad (14)\end{aligned}$$

As in the CSC system, the rate of s_c at user 1 becomes

$$\begin{aligned}\tilde{Z}_1 &= \mathbb{E}\left[\log_2\left(1 + \frac{|h_{1,1}|^2\gamma_c}{|h_{1,1}|^2\gamma + \beta\gamma + 1}\right)\right]\\ &= \mathbb{E}\left[C\left(|h_{1,1}|^2\frac{\gamma_c+\gamma}{\beta\gamma+1}\right)\right] - \mathbb{E}\left[C\left(|h_{1,1}|^2\frac{\gamma}{\beta\gamma+1}\right)\right]\\ &= \mathcal{C}_1\left(\frac{\psi(\gamma_c+\gamma)}{\beta\gamma+1}\right) - \mathcal{C}_1\left(\frac{\psi\gamma}{\beta\gamma+1}\right). \quad (15)\end{aligned}$$

Note that we do not need to find the rate of s_c at user 2 as s_c is not decoded and considered as the background noise in (14) at user 2 in the non-CSC system.

At user c, the rate of s_c is given by

$$\begin{aligned}\tilde{Z}_c &= \mathbb{E}\left[\log_2\left(1 + \frac{|h_{c,1}|^2\gamma_c}{|h_{c,1}|^2\gamma + \alpha\gamma + 1}\right)\right]\\ &= \mathcal{C}_1\left(\frac{\alpha(\gamma_c+\gamma)}{\alpha\gamma+1}\right) - \mathcal{C}_1\left(\frac{\alpha\gamma}{\alpha\gamma+1}\right). \quad (16)\end{aligned}$$

Thus, the extra rate using SC to support user c by BS 1 is given by $\tilde{R}_{ex} = \min\{\tilde{Z}_1, \tilde{Z}_c\}$. The sum rate of the non-CSC system is $\tilde{R}_1 + \tilde{R}_2 + \tilde{R}_{ex}$.

The sum rate[3] to near users in the DSC-SC system is the same as that in the non-CSC system. Due to DSC, we need to use order statistics. Let $|h_c|^2 = \max\{|h_{c,1}|^2, |h_{c,2}|^2\}$. Then, from (16), the rate of s_c to user c becomes

$$\hat{Z}_c = \mathbb{E}\left[\log_2\left(1 + \frac{|h_c|^2\gamma_c}{|h_c|^2\gamma + \alpha\gamma + 1}\right)\right]. \quad (17)$$

Denote by $f(x)$ and $F(x)$ the probability density function (pdf) and cummulative distribution function (cdf) of $|h_{c,j}|^2$, respectively. Then, since $f(|h_c|^2 = x) = 2F(x)f(x) = \frac{2}{\alpha}\left(e^{-\frac{x}{\alpha}} - e^{-\frac{2x}{\alpha}}\right)$, $x \geq 0$, it can be shown that

$$\begin{aligned}\hat{Z}_c = {}& 2\mathcal{C}_1\left(\frac{\alpha(\gamma_c+\gamma)}{\alpha\gamma+1}\right) - \mathcal{C}_1\left(\frac{\alpha(\gamma_c+\gamma)}{2(\alpha\gamma+1)}\right)\\ &- 2\mathcal{C}_1\left(\frac{\alpha\gamma}{\alpha\gamma+1}\right) + \mathcal{C}_1\left(\frac{\alpha\gamma}{2(\alpha\gamma+1)}\right). \quad (18)\end{aligned}$$

The extra rate using DSC-SC is given by $\hat{R}_{ex} = \min\{\tilde{Z}_1, \hat{Z}_c\}$.

[3]Assuming that $h_{c,1}$ and $h_{c,2}$ are independently and identically distributed (iid), the rates to users 1 and 2 are the same and become $\hat{R}_1 = \hat{R}_2 = \frac{R_1 + \tilde{R}_2}{2}$ as only one of them performs SIC at a time.

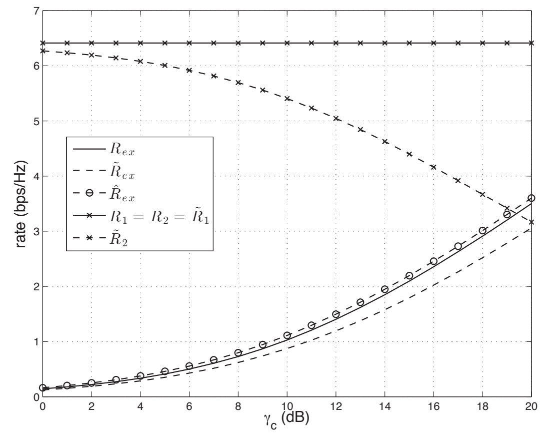

Fig. 2. $R_1 = R_2 = \tilde{R}_1$, $\tilde{R}_2$, R_{ex}, and $\tilde{R}_{ex}$ vs γ_c.

IV. Numerical Results

In this section, we present numerical results under symmetric channel conditions in **A1)** and **A2)**. We assume that the distance between user c and BS 1 or 2, denoted by d_c, is normalized such that $\alpha = 1$. Let d denote the distance between BS 1 (resp., BS 2) and user 1 (resp., user 2). Let $r = \frac{d}{d_c}$ and assume that the path loss exponent is 3.

Fig. 2 shows the extra rates to user c and rates to users 1 and 2 in the CSC, non-SC, and DCS-SC systems for different values of γ_c when $r = \frac{1}{4}$ (which results in $\psi = 64$ and $\beta = 0.186$) and $\gamma = 6$ dB. At user 2 in the non-CSC system, the signal to user c, s_c, becomes interference. Thus, $\tilde{R}_2$ decreases with γ_c. On the other hand, $R_1 = R_2 = \tilde{R}_1$ is independent of γ_c, since s_c is to be decoded and canceled using SIC. Consequently, the sum rate of the CSC system increases with γ_c and is higher than that of the non-CSC system, which is shown in Fig. 3. Note that the performance of the DSC-SC system is better than that of the non-CSC system due to DSC, but worse than that of the CSC system.

To see the impact of the distance between BS and near user, d, on the performance, the sum rates are obtained for different values of r with $\gamma = 6$ dB and $\gamma_c = 20$ dB. If NOMA with SC is not employed, the sum rate becomes $R_1 + R_2$. Fig. 4 shows that this sum rate decreases with r due to the propagation losses and the inter-cell interference. While this performance degradation is also valid for NOMA with SC, we can see that the CSC system provides a higher sum rate than the others for a wide range of r. Note that the gap between the sum rate of CSC and $R_1 + R_2$ is the rate to user c in the CSC system. According to Fig. 4, the rate to user c, which mainly depends on both γ_c and d_c (or α), is almost invariant regardless of r. From (8), as long as $Z_1, Z_2 > Z_c$, we have $R_{ex} = Z_c$.

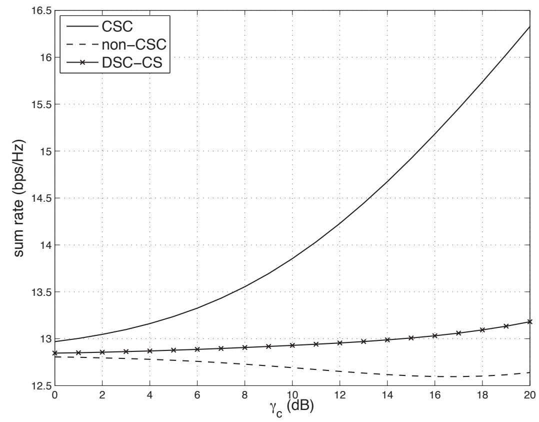

Fig. 3. Sum rates vs $\gamma_{\rm c}$.

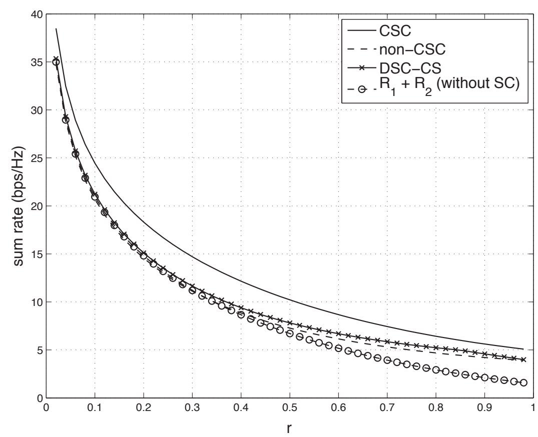

Fig. 4. Sum rates vs $r \in (0, 1)$.

Thus, while R_1 and R_2 decrease with r, $R_{\rm ex}$ would be almost independent of r.

V. Concluding Remarks

In this paper, we derived the sum rates for NOMA schemes with SC including the CSC system that does not require instantaneous CSI at BSs. It was shown that the CSC scheme with the Alamouti code can provide a cell-edge user with a reasonable transmission rate without degrading the rates to near users and increases the spectral efficiency.

Appendix A
Derivation of Achievable Rates

From [12], the pdf of the SNR of L-diversity maximal ratio combining (MRC) over Rayleigh fading is given by $f(\gamma) = \sum_{l=1}^{L} \frac{\pi_l}{\bar{\gamma}_l} e^{-\frac{\gamma}{\bar{\gamma}_l}}$, where $\bar{\gamma}_l$ is the average SNR of the lth branch and $\pi_l = \prod_{k=1,k\neq l}^{L} \frac{\bar{\gamma}_l}{\bar{\gamma}_l - \bar{\gamma}_k}$. The achievable rate becomes

$$\mathbb{E}[C(\gamma)] = \sum_{l=1}^{L} \pi_l \mathcal{C}_1(\bar{\gamma}_l). \tag{19}$$

Note that (19) is identical to that in [10] and valid for both the cases of unequal branch gains and of correlated gains (in this case, $\bar{\gamma}_l$ is the lth eigenvalue of the covariance matrix of the channel gain vector).

Since (19) is valid only for distinct branch SNRs, a result in [11] needs to be used for the ergodic capacity when $\bar{\gamma}_l = \bar{\gamma}$ for all l (i.e., equal branch SNR). For the case of $L = 2$, however, we derive a different expression in this appendix based on (19). For convenience, let $\bar{\gamma}_1 = x + \delta$ and $\bar{\gamma}_2 = x$, where $\delta > 0$. Then, using a Taylor series expansion, we have

$$\begin{aligned}\mathbb{E}[C(\gamma)] &= \frac{(x+\delta)\mathcal{C}_1(x+\delta) - x\mathcal{C}_1(x)}{\delta} \\ &= \frac{\delta\mathcal{C}_1(x) + \delta x \mathcal{C}_1'(x) + O(\delta^2)}{\delta},\end{aligned} \tag{20}$$

where $\mathcal{C}_1'(x) = \frac{d\mathcal{C}_1(x)}{dx}$. As $\delta \to 0$, we have $\lim_{\delta\to 0} \mathbb{E}[C(\gamma)] = \mathcal{C}_1(x) + x\mathcal{C}_1'(x)$. Using the properties of the exponential integral, $E_n(x)$, we can confirm the following result:

$$\mathcal{C}_1(x) + x\mathcal{C}_1'(x) = C_2(x), \tag{21}$$

which is the ergodic capacity with 2-fold MRC of equal gains.

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