Performance Analysis of NOMA Beamforming Multiple Users Relay Systems

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***Abstract*—In order to improve performance of multiple users (MUs) systems, several relays are deployed to help a base station (BS) decode and forward signals to end users. We propose that the BS utilize a beamforming approach to transmit its signal to relays, and then relays forward the received signals to users by non-orthogonal multiple access (NOMA) scheme. The system performance is shown through a close-form outage probability over Rayleigh fading channel with assumption of perfect successive interference cancellation. The calculation results are compared with simulation results to verify our theoretical analysis. Furthermore, the proposed combination of NOMA and beamforming method is compared with the conventional orthogonal multiple access method and an impact of imperfect channel state information on the system performance is also discussed.**

***Index Terms*—Non-orthogonal multiple access, close-form outage probability, Successive interference cancellation.**

I. Introduction

The non orthogonal multiple access (NOMA) is to use power domain for multiple access, the NOMA applies superposition codes at transmitters and signal processing, such as successive interference cancellation (SIC) method to detect the desired signals at receivers [1]. The SIC method decodes the received signal, and then removes the interference from another user. In the case of downlink multiple users (MUs) NOMA system, the users which have better channel condition is allocated with low transmit power, whereas the users which have worse channel conditions is allocated with high transmit power [2], [3]. This scheme is to keeps a balance between throughput and fairness of all users [4]. Furthermore, the NOMA system allocates the transmit power of every user based on their priorities, the user with higher priority is allocated with more power [5], [6].

Different to orthogonal multiple access (OMA) scheme in which multiple users share radio resources, either in time, frequency or code, the NOMA system provides better fairness, even for the users which have weaker channel gains. The performance of NOMA has been researching by many researchers in different scenarios. The previous researches is summarized as follows.

In [7], a downlink MUs NOMA system where all users are located randomly, is investigated, and then the close-forms of outage probability and the ergodic capacity are derived. In [8], both downlink and uplink of NOMA system are investigated, and . The dynamic power allocation is proposed under condition of QoS for different users. The result in the paper indicated that the proposed method can provide more fairness for all users. Similarly, the outage performance as well as the ergodic capacity are analyzed under condition of fairness quality of all users in [9].

Moreover, in [10], the cognitive radio with NOMA is discussed, and the power allocation coefficient is decided based on the pre-defined requirements of QoS of users. In [11] and [12], the NOMA is combined with multiple input multiple output (MIMO) multiple users (MUs) systems to improve the performance of MUs.

According to applying NOMA technology, the bandwidth efficiency, and then the throughput of MUs systems is improved. This characteristic shows that NOMA is a one of suitable technologies for MUs system. Furthermore, application of NOMA technology can provide an ultrahigh connectivity for many devices by the non-orthogonal properties of NOMA. Especially, the low complexity of NOMA systems compared with other multiple access methods is an attractive feature of NOMA [13].

In order to improve performance of MUs systems, several relays are deployed to help a base station (BS) decode and forward signals to end users. We propose that the BS utilize a beamforming approach to transmit its signal to relays, and then relays forward the received signals to users by NOMA technology. The contributions of the paper are summarized as follows.

- We propose combination of beamforming at the BS and NOMA technology at the relay to improve the performance of downlink MUs MIMO relay systems, and the performance of system is analyzed theoretically.
- The close-form expression of outage probability is de-

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rived to evaluate the performance of system. The simulation result is also expressed to confirm the proposed mathematical close-form expressions.

Organization of the rest of the paper is explained as follows. Section II depicts the system model, and the performance of downlink MU NOMA relay system is analyzed in Section III. Calculation results are showed in Section IV, and Section V gives the conclussion of the work.

II. Downlink MU relay systems

A. System Model

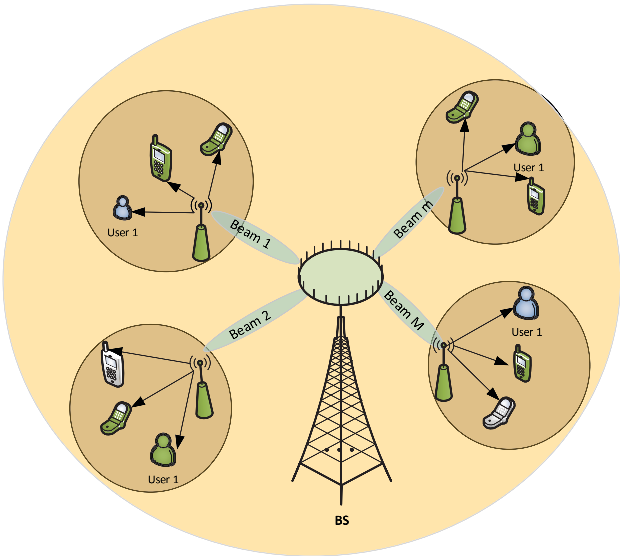

Fig. 1. System model of downlink MUs relay systems

The system model of downlink MUs relay systems is depicted in Fig.1, the relays (R) are located between a base station (BS) and users to forward signals of BS to users. Users are grouped into several clusters, and one relay serves one cluster. The direct link from the BS to each user is unavailable due to far distance and showing fading. We assume that the number of antennas at the BS and every relay are respectively N_t and N_r; The number of clusters equals the number of relays as M, and the number of users in each cluster equals as N. According to the NOMA technology and DF protocol, the SIC is performed at the relay and users to remove the inter-user interference (IUI). $\mathbf{x}_{\mathrm{S},m} = [x_{m,1}, \cdots, x_{m,N}]^T$ with $m \in [1, \ldots, M]$, $n \in [1, \ldots, N]$ and $\mathbb{E}\{|\mathbf{x}_{\mathrm{S},m}|^2\} = 1$ denotes the transmit signals of the BS for all the users in the mth cluster, and before transmitting to the relay, it is multiplied by a $N_t \times 1$ beamforming vector $\mathbf{w}_m$, which is assumed to be normalize $\|\mathbf{w}_m\|^2 = 1$.

B. Received signals of users

Assuming that, the minimum mean squared error (MMSE) is utilized, the channel matrix and the channel coefficient are denoted by $\mathbf{h}_m$ and g_n, respectively. In addition, $\Omega_{\mathcal{A}}$ with $\mathcal{A} \in \{\mathrm{SR}_m, \mathrm{R}_m\mathrm{D}_n\}$ is the channel gain norm of the $\mathbf{h}_m$.

The zero-force beamforming (ZFBF) method is applied to the BS to keep a trade-off between the complexity and the performance of system. The weight $\mathbf{w}_m$ for the mth cluster is designed to mitigate the other clusters's interference.

$\mathbf{w}_m$ is a projection of $\mathbf{h}_m$ which is in the null space of the interference direction of the mth cluster. Thus, owing to cancel the inter-cluster interference while maximizing the channel gain, $\mathbf{w}_m$ is mathematically given as

$$\mathbf{w}_m = \frac{\mathbf{\Pi}_m \mathbf{h}_m}{\|\Pi_m \mathbf{h}_m\|}, \tag{1}$$

where $\mathbf{\Pi}_m = \mathbf{I}_N - \mathbf{H}_m(\mathbf{H}_m^H \mathbf{H}_m)^{-1}\mathbf{H}_m^H$ and the matrix $\mathbf{H}_m$ is given as

$$\mathbf{H}_m = [\mathbf{h}_1, \mathbf{h}_2, \cdots, \mathbf{h}_{m-1}, \mathbf{h}_{m+1}, \cdots, \mathbf{h}_M]^T. \tag{2}$$

Consequently, one dimension of $\mathbf{H}_m$ is greater than zero, it means that the signals can be transmitted to the relay.

$$\mathbf{h}_m^H \mathbf{w}_j = 0, \forall m \neq j. \tag{3}$$

The signals which is transmitted toward the mth cluster is described by

$$\mathbf{x}_{\mathrm{S},m} = \mathbf{w}_m \sum_{n=1}^{N} \sqrt{a_n P_{\mathrm{S}}} x_n, \tag{4}$$

where $P_{\mathrm{S}} = \mathbb{E}\{|\mathbf{x}_{\mathrm{S},m}|^2\}$ ss the power allocation coefficient of the (m, n)th user, moreover a_n satisfies $\sum_{n=1}^{N} a_n = 1$.

Because $\mathbf{x}_{\mathrm{S}}$ is broadcast to all relays simultaneously, the received signal at the relays can be represented as

$$\mathbf{y}_R = \underbrace{\mathbf{h}_m \mathbf{w}_m \sum_{n=1}^{N} \sqrt{a_n P_{\mathrm{S}}} \mathbf{x}_{\mathrm{S},m}}_{m\text{th beam}} + \underbrace{\mathbf{h}_m \mathbf{w}_j \sum_{m=1}^{M} \sqrt{a_k P_{\mathrm{S}}} \mathbf{x}_{\mathrm{S}}}_{\text{other beams}} + \mathbf{n}_{m,n}, \tag{5}$$

where $x_{\mathrm{S}} = [\mathbf{x}_{\mathrm{S},1}, \cdots, \mathbf{x}_{\mathrm{S},m-1}, \mathbf{x}_{\mathrm{S},m+1}, \cdots, \mathbf{x}_{\mathrm{S},M}]^T$.

We assume that beamforming is perfect, the received signal at the mth relay is represented as

$$\begin{aligned} \mathbf{y}_{m,R} &= \mathbf{h}_m \mathbf{w}_m \sum_{n=1}^{N} \sqrt{a_n P_{\mathrm{S}}} x_m + \mathbf{n}_{m,n} \\ &= \underbrace{\mathbf{h}_m \mathbf{w}_m \sqrt{a_n P_{\mathrm{S}}} x_m}_{\text{desired signal of } (m,n)\text{th user}} + \underbrace{\mathbf{h}_m \mathbf{w}_m \sum_{i=n+1}^{N} \sqrt{a_{m,i} P_{\mathrm{S}}} x_{m,i}}_{\text{interference of other user}} \\ &\quad + \underbrace{\mathbf{h}_m \mathbf{w}_m \sum_{k=1}^{n-1} \sqrt{\xi_1 a_{m,k} P_{\mathrm{S}}} x_{m,k}}_{\text{interference of imperfect SIC}} + \mathbf{n}_m, \end{aligned} \tag{6}$$

where $\mathbf{n}_m = [n_1, \cdots, n_N] \in \mathbb{C}^{1 \times N}$ with $n_m \sim \mathcal{CN}(0, \sigma_m^2)$ is an i.i.d additive white Gaussian noise (AWGN) at the mth relay. In the case of perfect SIC, the interference term $\mathbf{h}_m \mathbf{w}_m \sum_{k=1}^{n-1} \sqrt{a_k P_{\mathrm{S}}} x_k$ equals to zero.

After receiving the signals, the relays re-encode and forward the signal to the users. The received signal of the (m,n)th user, it means the received signal of the nth user in the mth cluster, is represented as follows.

$$y_{D_n} = \underbrace{g_n\sqrt{b_n P_{\rm R}}x_m}_{\text{desired signal of } (n)\text{th user}} + \underbrace{g_n \sum\nolimits_{i=n+1}^{N} \sqrt{b_i P_{\rm R}}x_i}_{\text{interference of other user}} + \underbrace{\sum\nolimits_{k=1}^{n-1} \sqrt{\xi_2 b_k P_{\rm R}} g_n x_k}_{\text{interference of imperfect SIC}} + w_{D_n}. \quad (7)$$

With assumption of $|g_1|^2 <, \cdots, < |g_N|^2$, the interference from another user which has stronger transmit power, i.e., the interference of $(k = 1, \ldots, n-1)$th users, is deleted by the SIC process. γ_{R_n} and γ_{D_n} denote the signal to interference plus noise ratio (SINR) of (m,n)th user at the mth relay and at the end user, respectively. From (6), we have

$$\gamma_{R_n} = \frac{P_{\rm S} a_n |\mathbf{h}_m \mathbf{w}_m|^2}{\sum_{i=n+1}^{N} P_{\rm S} a_i |\mathbf{h}_m \mathbf{w}_m|^2 + \sigma_{R,n}^2}. \quad (8)$$

From (7), when $(b_i < b_n)$ the SINR of the (m,n)th user at the end user in the case of perfect SIC is represented as

$$\gamma_{D_n} = \frac{P_{\rm R} b_n |g_n|^2}{\sum_{i=n+1}^{N} b_i P_{\rm R} |g_n|^2 + \sigma_{D,n}^2}. \quad (9)$$

Noted that, for the DF protocol, the end-to-end SINR is the smaller one among the two hops $\rm BS \to R_m$ and $\rm R_m \to D_{\mathit{n}}$, it means

$$\gamma_{e2e} = \min(\gamma_{\rm R_n}, \gamma_{\rm D_n}). \quad (10)$$

III. Performance Analysis

A. Outage Probability

The outage probability (OP) of the considered (m,n)th user is derived in this section. The OP is known as the probability when instantaneous transmission rate of any user is smaller than the required data rate. r_1, r_n (bit/s/Hz) denote the required data rate of the hop $\rm BS \to R_m$ and $\rm R_m \to D_{\mathit{n}}$, respectively. We set $r_1 = r_n = r$ for simply, thus the OP is given as

$$\begin{aligned}\mathrm{OP}_{\rm D_n} &= \Pr\left[\frac{1-\alpha}{2}\log_2\Big(1+\gamma_{e2e}\Big)\right] \\ &= \Pr\left(\gamma_{e2e} < 2^{\frac{2r}{1-\alpha}} - 1\right)\end{aligned} \quad (11)$$

Substitute γ_{e2e} in (10) into (11) we have OP of nth user in mth cluster as

$$\begin{aligned}\mathrm{OP}_{\rm D_n} &= \Pr\Big[\min(\gamma_{\rm R_n}, \gamma_{\rm D_n}) < \gamma_{\rm th}\Big] \\ &= 1 - \Pr\Big(\gamma_{\rm R_n} \geq \gamma_{\rm th}, \gamma_{\rm D_n} \geq \gamma_{\rm th}\Big),\end{aligned} \quad (12)$$

where $\gamma_{\rm th} = 2^{\frac{2r}{1-\alpha}} - 1$.

Applying SNR equations which is represented in (8) and (9), we can calculate the OP under the perfect SIC as in (13) which is shown in the next page.

Now, let us denote, $X = |\mathbf{h}_m \mathbf{w}_m|^2$ and $Y = |g_n|^2$ for notational convenience.

Hence the cumulative distribution function (CDF) and probability density function (PDF) of X and Y are given as

$$F_X(x) = 1 - \exp\left(\frac{-x}{(1-\rho)\Omega_{\rm SR}}\right) \sum_{k=0}^{K-1} \frac{1}{k!}\left(\frac{x}{(1-\rho)\Omega_{\rm SR}}\right)^k, \quad (14)$$

$$f_X(x) = \frac{x^{K-1}}{\Gamma(K)[(1-\rho)\Omega_{\rm SR}]^K} \exp\Big(-\frac{x}{(1-\rho)\Omega_{\rm SR}}\Big). \quad (15)$$

Based on the ordered statistics, the PDF of channel gain $|g_n|^2$ can be written as [14, eq, (6.58)].

$$f_Y(y) = N f_{|g_j|^2}(x)[F_{|g_j|^2}(y)]^{N-1}. \quad (16)$$

where

$$f_{|g_j|^2}(y) = \frac{1}{(1-\rho)\Omega_{\mathrm{RD}_j}} \exp\Big(-\frac{y}{(1-\rho)\Omega_{\mathrm{RD}_j}}\Big), \quad (17)$$

$$F_{|g_j|^2}(y) = 1 - \exp\Big(-\frac{y}{(1-\rho)\Omega_{\mathrm{RD}_j}}\Big). \quad (18)$$

After performing some manipulations and simplifications, we have the PDF of $|g_n|^2$ on the second hop as

$$f_Y(y) = \sum_{j=1}^{N} \binom{N}{j} \frac{(-1)^{j-1} j}{(1-\rho)\Omega_{\mathrm{RD}_j}} \exp\left(-\frac{jx}{(1-\rho)\Omega_{\mathrm{RD}_j}}\right). \quad (19)$$

From (19) the CDF of Y is given by

$$F_Y(y) = \sum_{j=1}^{N} \binom{N}{j} (-1)^{j-1} \left[1 - \exp\left(-\frac{jx}{(1-\rho)\Omega_{\mathrm{RD}_j}}\right)\right]. \quad (20)$$

According to the properties of CDF is that, $F_Y(\infty) = 1$. We can let $y \to \infty$ into (20), lead to have result as $\sum_{j=1}^{N}\binom{N}{j}(-1)^{j-1} = 1$. Thus, we can rewrite (20) as

$$F_Y(y) = 1 - \sum_{j=1}^{N} \binom{N}{j} (-1)^{j-1} \exp\left(-\frac{jy}{(1-\rho)\Omega_{\mathrm{RD}_j}}\right). \quad (21)$$

Base on CDF and PDF of both hops, the OP is derived as follows.

(13) can be rewritten as

$$\begin{aligned}\mathrm{OP}_{\rm D_n} &\triangleq 1 - \Pr\left(X \geq \frac{\gamma_{\rm th}\sigma_{\rm R}^2}{P_{\rm S}(a_n - \gamma_{\rm th}\tilde{a})}\right) \Pr\left(Y \geq \frac{\gamma_{\rm th}\sigma_{{\rm D},n}^2}{P_{\rm R}(b_n - \gamma_{\rm th}\tilde{b})}\right) \\ &= 1 - \Big[1 - F_X(x)\Big]\Big[1 - F_Y(y)\Big]\end{aligned} \quad (22)$$

where $x = \frac{\gamma_{\rm th}\sigma_{\rm R}^2}{P_{\rm S}(a_n - \gamma_{\rm th}\tilde{a})}$ and $y = \frac{\gamma_{\rm th}\sigma_{{\rm D},n}^2}{P_{\rm R}(b_n - \gamma_{\rm th}\tilde{b})}$ with $\tilde{a} = \sum_{i=n+1}^{N} a_i$ and $\tilde{b} = \sum_{i=n+1}^{N} b_i$. The $\triangleq$ has the mean that, the $a_n > \gamma_{\rm th}\tilde{a}$ and $b_n > \gamma_{\rm th}\tilde{b}$ should meet. Otherwise, $a_n \leq \gamma_{\rm th}\tilde{a}$ and $b_n \leq \gamma_{\rm th}\tilde{b}$ the outage probability always occurs, because,

$$\mathrm{OP}_{\mathrm{D}_n} = 1 - \Pr\left(\frac{P_{\mathrm{S}} a_n |\mathbf{h}_m \mathbf{w}_m|^2}{\sum_{i=n+1}^{N} P_{\mathrm{S}} a_i |\mathbf{h}_m \mathbf{w}_m|^2 + \sigma_{\mathrm{R}}^2} \geq \gamma_{\mathrm{th}}, \frac{P_{\mathrm{R}} b_n |g_n|^2}{\sum_{i=n+1}^{N} b_i P_{\mathrm{R}} |g_n|^2 + \sigma_{\mathrm{D},n}^2} \geq \gamma_{\mathrm{th}}\right), \tag{13}$$

we only consider the $X, Y \in (0, \infty)$. Hence the allocated power for D_n is more than the others.

To get the close-form for (22) we replace CDF from (14) and (21) into (22). Finally, the OP is expressed as

$$\mathrm{OP}_{\mathrm{D}_n} = 1 - \left[\exp\left(-\frac{x}{(1-\rho)\Omega_{\mathrm{SR}}}\right) \sum_{k=0}^{K-1} \frac{1}{k!} \left(\frac{x}{(1-\rho)\Omega_{\mathrm{SR}}}\right)^k\right] \times \left[\sum_{j=1}^{N} \binom{N}{j} (-1)^{j-1} \exp\left(-\frac{jy}{(1-\rho)\Omega_{\mathrm{RD}_j}}\right)\right]. \tag{23}$$

IV. Calculation Results

The calculation results are provided in this section to discuss the performance of the NOMA beamforming relay system based on the OP. The simulation parameter is set as: The minimal required data rates of D_n are given as $r_1 = r_2 = r_3 = 1$ [b/s/Hz]. The number of relays M is 3, and every cluster has 3 users which are served instantaneously by one relay. The power allocation coefficient of the (m, n)th user a_n is calculated by the following equation, $a_n = (N - n + 1)/\mu$, where μ should satisfy $\sum_{n=1}^{N} \sqrt{a_n P_S} = 1$. The power allocation coefficient of both the BS and the relay is assumed to be the same for simply.

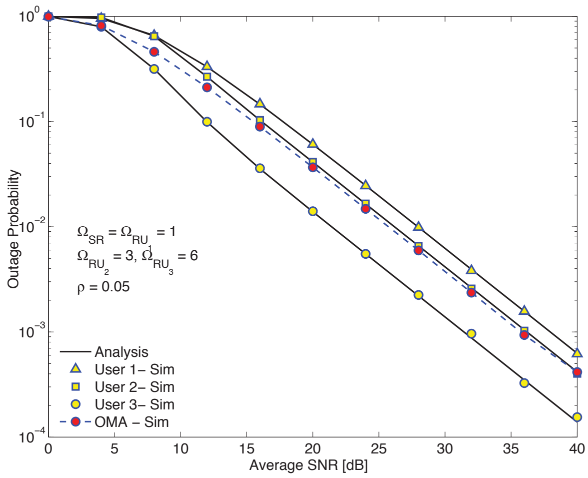

Fig. 2. The OP versus SNRs of every user with $a_1 = 0.6, a_2 = 0.3, a_3 = 0.1$

Fig.2 presents the OP of every user via SNR in dB. From Fig. 2 we can recognize that although the lowest transmit power is allocated for the 3^{th} user, its performance is the best. The reason is explained as that, the 3^{th} user is the closest to the relay, it means the channel gain between it and the relay is the largest. Moreover, the inter-user interference (IUI) at the 3^{th} user is completely removed by SIC processing, whereas the IUI at the other users is still remained. We can also know that the analytical results match perfectly with the calculation results; The performance of the 1^{st} and 2^{nd} users is lower, however the performance of 3^{th} user is higher than that of orthogonal multiple access (OMA) system.

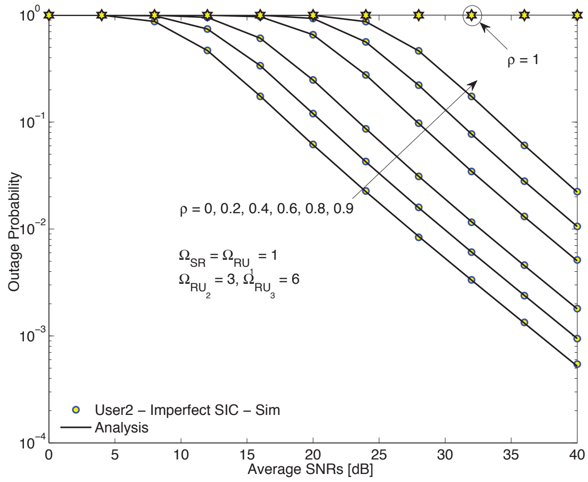

Fig. 3. The OP versus average SNR in case of difference correlation coefficients and $a_1 = 0.6, a_2 = 0.3, a_3 = 0.1$, $\xi_1 = \xi_2 = 0.05$.

In Fig 3, we discuss the effects of channel estimation error on the OP of system. The correlation coefficient ρ, $(0 \leq \rho \leq 1)$, is the correlation coefficient between the true channel state information (CSI) and the error CSI. When the ρ becomes smaller, it means the estimated CSI is closer to the true CSI. The calculation results show that when the ρ increases meaning the estimation error increases, the OP of system is worse. Especially, when $\rho = 1$ the system performance is always outage.

V. Conclusions

In this paper, the combination of NOMA and beamforming was proposed for downlink MU systems, and the performance of the system was analyzed theoretically based on Rayleigh distribution. The close-form expressions of OP are derived and compared with the simulation results. The perfect match between calculation and simulation results verified the mathematical analysis method. Moreover, the proposed combination of two signal processing methods, such as NOMA and beamforming, is compared with the conditional OMA system, and the advantages of each method were discussed. The perfect and imperfect CSI were taken into consideration, and the effect of CSI on the performance of system was analyzed. However, the imperfect beamforming as well as the imperfect SIC should be discussed, and we leave these issues for the future work.

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