On the Spectral Efficient Nonorthogonal Multiple Access Schemes

Jinho Choi
School of Electrical Engineering and Computer Science
Gwangju Institute of Science and Technology (GIST), Korea
Email: jchoi0114@@gist.ac.kr

***Abstract*—In this paper, we introduce a nonorthogonal multiple access scheme, called relay-aided multiple access (RAMA), which is based on network coding. This scheme is compared with a well-known scheme, nonorthogonal multiple access (NOMA), which is based on superposition coding. Both the schemes can increase the spectral efficiency by supporting two users in the same frequency band and time slot. To compare them, we consider the sum rate, which is the sum of achievable rates of uplink and downlink transmissions of two users, and study a sum rate maximization problem with transmission power constraints. Based on sum rate analysis, we can show that each scheme can perform better than the other under different conditions. Thus, we can enjoy a degree of freedom to choose one of them depending on conditions to improve the spectral efficiency.**

***Index Terms*—nonorthogonal multiple access; relay-aided multiple access; achievable rates**

I. Introduction

Nonorthogonal multiple access (NOMA) has been studied for cellular systems in order to improve the spectral efficiency [1]–[4]. As opposed to orthogonal multiple access (OMA), in NOMA, multiple users of different channel gains can be supported in the same frequency band and time slot (or radio resource block) simultaneously by exploiting the power domain. For example, if there are one user of high channel gain (for convenience, this user is referred to as user 1) and the other user of low channel gain (this user is referred to as user 2), a base station (BS) can transmit two signals to both users simultaneously. The BS usually allocates a high transmission power to user 2 and a low transmission power to user 1. From this, at user 1, the signal to user 2 might be decodable. Thus, user 1 decodes the signal to user 2 first and then decodes his/her signal after subtracting the decoded signal to user 2. At user 2, the signal to user 2 can be decoded without significant interference from the signal to user 1, which is weak. Clearly, in NOMA, by making use of superposition coding [5] together with successive interference cancellation (SIC) [6], the spectral efficiency can be higher than that in OMA. NOMA can be extended for downlink coordinated two-point systems [7] and multiple input multiple output (MIMO) systems [4].

Exploiting the notion of network coding [8], various approaches for two-way relay transmission (TWRT) are studied in [9]–[11] for a higher spectral or energy efficiency. In cellular systems, it is possible to use a user closer to the BS as a relay node in delivering signals between the BS and another user who is not close to the BS. The former and latter users might be user 1 and user 2, respectively. The resulting scheme is referred to as relay-aided multiple access (RAMA), where user 1 becomes a relay node for user 2.

A common feature of NOMA and RAMA is that two users can be supported in the same resource block. Thus, they may have higher spectral efficiencies than OMA. In this paper, we study the sum rates of NOMA and RAMA once we present their system models for both downlink and uplink transmissions. Based on the sum rate analysis, we can characterize each scheme's advantages over the other.

II. System Models

In this section, we present system models for NOMA and RAMA that can support two users in the same frequency band and time slot.

A. NOMA

Suppose that there are two users who are allocated in the same resource block for uplink and downlink transmissions in NOMA systems. For convenience, we assume that user 1 is closer to a BS than user 2 as illustrated in Fig. 1. The channel coefficient between the BS and user k is denoted by h_k. Throughout the paper, we consider a time division duplexing (TDD) based system for uplink and downlink transmissions. Thus, we assume the same channel coefficients for uplink and downlink transmissions.

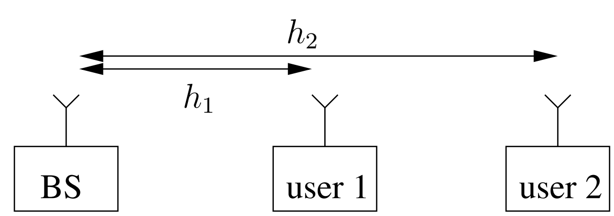

Fig. 1. A system model for NOMA.

Denote by s_k the downlink signal to user k. In NOMA, the BS is to transmit a superposition of two signals, i.e., $s_1 + s_2$, to users 1 and 2 simultaneously. Then, the received signal at user k, which is denoted by y_k, is given by

$$\begin{aligned} y_1 &= h_1(s_1 + s_2) + n_1 \\ y_2 &= h_2(s_1 + s_2) + n_2, \end{aligned} \tag{1}$$

where $n_k \sim \mathcal{CN}(0,1)$ is the background noise at user k. Here, $\mathcal{CN}(\mu, \sigma^2)$ represents the distribution of circularly symmetric complex Gaussian (CSCG) random variable with mean μ and variance σ^2. For normalization purposes, we assume that the variance of the background noise is unity. In general, it is assumed that the signal power of s_2 is higher than that of s_1, i.e., $P_2 > P_1$, where $P_k = \mathbb{E}[|s_k|^2]$ (we also assume that $\mathbb{E}[s_k] = 0$), in NOMA. Here, $\mathbb{E}[\cdot]$ stands for the statistical expectation. Thus, at user 1, it is expected to decode s_2 first. Then, after removing s_2 from y_1, s_1 is to be decoded according to the notion of SIC. At user 2, s_2 is decoded with s_1 as interference.

For uplink transmissions in TDD mode, we assume that both the users transmit their signals simultaneously. Denote by c_k the uplink signal from user k. Then, the received signal at the BS is given by

$$z = h_1 c_1 + h_2 c_2 + n, \tag{2}$$

where $n \sim \mathcal{CN}(0,1)$ is the background noise at the BS. Let $Q_k = \mathbb{E}[|c_k|^2]$ with the assumption that $\mathbb{E}[c_k] = 0$.

It is noteworthy that the downlink channel is a typical broadcast (BC) channel [5]. On the other hand, the uplink channel is a typical multiple access channel (MAC).

B. RAMA

It is possible to exploit the notion of two-way relay with network coding in supporting two users in the same radio resource block as in NOMA. Since user 1 is closer to the BS, user 1 can work as a relay node in delivering messages between the BS and user 2. The approach consists of two phases as illustrated in Fig. 2. In Phase I, the BS and user 2 transmit the signals to user 1. The received signal at user 1 during Phase I is given by

$$x = h_1(s_1 + s_2) + g c_2 + n_1, \tag{3}$$

where g is the channel coefficient between users 1 and 2, and $n_1 \sim \mathcal{CN}(0,1)$ is the background noise at user 1 during Phase I. The BS is to transmit the sum of the two downlink signals, s_1 and s_2, while user 2 is to transmit her uplink signal, c_2. In Phase II, user 1 broadcasts a superposition of c_1 and $\psi_2 = s_2 \oplus c_2$. Here, ψ_2 is an XORed version of s_2 and c_2. The received signals at the BS and user 2, denoted by z_B and z_2, respectively, are given by

$$\begin{aligned} z_\mathrm{B} &= h_1(c_1 + \psi_2) + n_\mathrm{B} \\ z_2 &= g(c_1 + \psi_2) + n_2, \end{aligned} \tag{4}$$

where n_B and $n_2 \sim \mathcal{CN}(0,1)$ are the background noise terms at the BS and user 2, respectively, during Phase II. At the BS, once c_1 and ψ_2 are successfully decoded, c_2 can be obtained by taking the XOR operation with the known signal, s_2, as $\psi_2 \oplus s_2 = (c_2 \oplus s_2) \oplus s_2 = c_2$. Similarly, once user 2 can decode c_1 and ψ_2, s_2 can be obtained by $\psi_2 \oplus c_2 = (c_2 \oplus s_2) \oplus c_2 = s_2$.

It is noteworthy that while ψ_2 is expressed as $s_2 \oplus c_2$ for notational convenience, it does not mean that $s_2, c_2 \in \{0,1\}$.

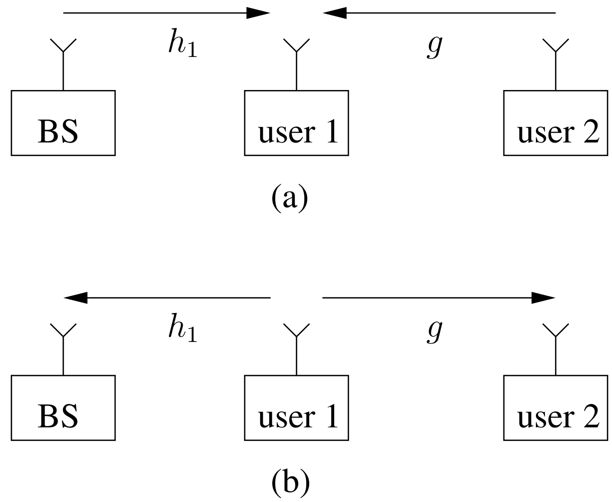

Fig. 2. A system model for RAMA: (a) Phase I; (b) Phase II.

To be precise, both s_2 and c_2 are codewords that are modulated with a common constellation, which is denoted by $\mathcal{S}_2$. Once s_2 and c_2 are successfully decoded at user 1 from x in (3), their bits are XORed. Then, it is modulated with the constellation $\mathcal{S}_2$. Thus, $\psi_2 \in \mathcal{S}_2$. However, as shown above, for notational convenience, the XORed version of s_2 and c_2, ψ_2, is represented as $\psi_2 = s_2 \oplus c_2$ in this paper.

The main advantage of RAMA over NOMA is that the transmission power from user 2 for uplink transmissions can be low by relay transmissions using network coding [12] (note that in NOMA, user 2 directly transmits her uplink signal, c_2, to the BS). On the other hand, since NOMA exploits power differences in downlink transmissions, it may provide a better spectral efficiency than RAMA in transmitting s_1 and s_2 using superposition coding. Thus, it is interesting to compare their sum rates, which will be discussed in Section III.

III. Sum Rate Maximization

In this section, we consider the sum rates of NOMA and RAMA for downlink and uplink transmissions. For tractable analysis, we assume that s_k and c_k are independent Gaussian signals.

A. Sum Rate of NOMA

In NOMA, we can employ a BC channel model [5] for downlink transmissions. Let R_k be the achievable rates from the BS to user k. Then, from [5], we have

$$\begin{aligned} R_1 &\le \log_2(1 + \alpha_1 P_1) \\ R_2 &\le \log_2\left(1 + \frac{\alpha_1 P_2}{\alpha_1 P_1 + 1}\right) \\ R_2 &\le \log_2\left(1 + \frac{\alpha_2 P_2}{\alpha_2 P_1 + 1}\right), \end{aligned} \tag{5}$$

where $\alpha_k = |h_k|^2$.

For uplink transmissions, we can consider a MAC model. Let U_k be the achievable rates from user k to the BS. From [5], we have

$$\begin{aligned} U_1 &\le \log_2(1+\alpha_1 Q_1) \\ U_2 &\le \log_2(1+\alpha_2 Q_2) \\ U_1+U_2 &\le \log_2(1+\alpha_1 Q_1+\alpha_2 Q_2). \end{aligned} \tag{6}$$

Thus, in order to maximize the sum rate, we can consider the following problem:

$$\begin{aligned} &\max_{P_k,Q_k} R_1+R_2+U_1+U_2 \\ &\text{subject to (5), (6), and} \\ &P_1+P_2 \le \bar{P},\ Q_1+Q_2 \le \bar{Q}, \end{aligned} \tag{7}$$

where $\bar{P}$ and $\bar{Q}$ are the total BS's transmission power and users' transmission power, respectively. Since the constraints in (5) only have the P_k's and those in (6) only have the Q_k's, the problem in (7) can be decoupled. For downlink transmissions, we have

$$\max_{P_k} R_1+R_2 \text{ subject to (5) and } P_1+P_2 \le \bar{P}. \tag{8}$$

For uplink transmissions, we have

$$\max_{Q_k} U_1+U_2 \text{ subject to (6) and } Q_1+Q_2 \le \bar{Q}. \tag{9}$$

Let us consider the maximization of downlink sum rate.

Property 1. *If $\alpha_1 > \alpha_2$, the optimal solution of the problem in (8) becomes*

$$P_1^* = \bar{P} \text{ and } P_2^* = 0.$$

Proof: We can show that

$$R_1+R_2 \le \log_2(1+\alpha_2\bar{P}) + \log_2\left(\frac{1+\alpha_1 P_1}{1+\alpha_2 P_1}\right).$$

Since the second term is an increasing function of P_1 if $\alpha_1 > \alpha_2$, the sum rate is maximized when $P_1^* = \bar{P}$ and $P_2^* = 0$. ■

Thus, in order to avoid zero rate for user 2, we need to consider a rate constraint that is given by

$$\log_2\left(1+\frac{\alpha_2 P_2}{\alpha_2 P_1+1}\right) \ge \bar{R}_2, \tag{10}$$

where $\bar{R}_2 > 0$ denotes the required minimum downlink rate for user 2. Note that R_1+R_2 is an increasing function of P_1 if $\alpha_1 > \alpha_2$ as shown in Property 1. From this, if there is a feasible power allocation under the constraint in (10) (i.e., $\bar{P} \ge \frac{2^{\bar{R}_2}-1}{\alpha_2}$ is satisfied), the maximum achievable sum rate becomes $\bar{R} = \bar{R}_1 + \bar{R}_2$, where $\bar{R}_1 = \log_2(1+\alpha_1 P_1(\bar{R}_2))$. Here, $P_1(\bar{R}_2) = \frac{1}{2^{\bar{R}_2}}\left(\bar{P} - \frac{2^{\bar{R}_2}-1}{\alpha_2}\right)$.

We now consider the maximization of uplink sum rate.

Property 2. *If $\alpha_1 > \alpha_2$, the problem in (9) becomes*

$$Q_1^* = \bar{Q} \text{ and } Q_2^* = 0.$$

Similarly, in order to avoid zero rate for user 2, we may need to consider the minimum required uplink rate for user 2, denoted by $\bar{U}_2$. If $\bar{Q} \ge \frac{2^{\bar{U}_2}-1}{\alpha_2}$ (i.e., a feasible solution exists to guarantee $U_2 \ge \bar{U}_2$), the maximum achievable sum rate becomes

$$\bar{U} = \bar{U}_1 + \bar{U}_2 = \log_2\left(1+(\alpha_1-\alpha_2)\bar{Q}_1(\bar{U}_2)+\alpha_2\bar{Q}\right),$$

where $\bar{Q}_1(\bar{U}_2) = \bar{Q} - \frac{2^{\bar{U}_2}-1}{\alpha_2}$.

B. Sum Rate of RAMA

Due to network coding in RAMA, we will assume that $R_2 = U_2$ in this section.

For Phase I, we can consider a MAC model. Thus, the achievable rates can be given by

$$\begin{aligned} R_1+R_2 &\le \log_2(1+\alpha(P_1+P_2)) \\ U_2 &\le \log_2(1+\beta Q_2) \\ R_1+R_2+U_2 &\le \log_2(1+\alpha_1(P_1+P_2)+\beta Q_2), \end{aligned} \tag{11}$$

where $\beta = |g|^2$.

For Phase II, we can consider a BC model. We assume that the transmission power to transmit $c_1+\psi_2$ is Q_1. Then, at the BS, we have the following achievable rates:

$$\begin{aligned} U_1 &\le \log_2(1+\alpha_1\omega Q_1) \\ U_2 &\le \log_2\left(1+\frac{\alpha_1(1-\omega)Q_1}{\alpha_1\omega Q_1+1}\right), \end{aligned} \tag{12}$$

where $0 \le \omega \le 1$. Here, ωQ_1 can be considered the power allocated to c_1, while $(1-\omega)Q_1$ to ψ_2. At user 2, we have

$$\begin{aligned} R_2 &\le \log_2(1+\beta(1-\omega)Q_1) \\ U_1 &\le \log_2\left(1+\frac{\beta\omega Q_1}{\beta(1-\omega)Q_1+1}\right). \end{aligned} \tag{13}$$

Property 3. *Let $\nu = \min\{\alpha_1, \beta\}$. Then, (12) and (13) reduce to the following:*

$$U_1 \le \log_2\left(1+\frac{\nu\omega Q_1}{\nu(1-\omega)Q_1+1}\right) \tag{14}$$

$$R_2 \le \log_2\left(1+\frac{\nu(1-\omega)Q_1}{\nu\omega Q_1+1}\right), \tag{15}$$

Proof: From (12) and (13), we can have (14) by the following inequalities:

$$\begin{aligned} \frac{\nu\omega Q_1}{\nu(1-\omega)Q_1+1} &\le \frac{\beta\omega Q_1}{\beta(1-\omega)Q_1+1} \\ \frac{\nu\omega Q_1}{\nu(1-\omega)Q_1+1} &\le \frac{\alpha_1\omega Q_1}{\alpha_1(1-\omega)Q_1+1} \le \alpha_1\omega Q_1. \end{aligned}$$

Similarly, we can also derive (15) from (12) and (13). ■

The maximization of sum rate can be formulated as

$$\begin{aligned} &\max_{P_k,Q_k,\omega} R_1+R_2+U_1+U_2 \\ &\text{subject to (11), (14), (15), and} \\ &P_1+P_2 \le \bar{P},\ Q_1+Q_2 \le \bar{Q},\ 0 \le \omega \le 1. \end{aligned} \tag{16}$$

Since we assume that $R_2 = U_2$, from (11), (14), and (15), the sum rate is bounded as

$$\begin{aligned} R_1+2R_2+U_1 \le\ &\log_2\left(1+\alpha_1\bar{P}+\beta Q_2\right) \\ &+\log_2\left(1+\frac{\nu\omega Q_1}{\nu(1-\omega)Q_1+1}\right). \end{aligned} \tag{17}$$

Since $\omega = 1$ is required to maximize the sum rate, we can see that $U_2 = R_2 = 0$, i.e., the downlink and uplink rates for user 2 are zero when the sum rate is maximized. To avoid this, we need to consider the minimum required rate for $U_2 = R_2$, which is denoted by $\bar{R}_2 > 0$. In this case, from (15) and (11), we have the following constraint:

$$\log_2\left(1 + \min\left\{\beta Q_2, \frac{\nu(1-\omega)Q_1}{\nu\omega Q_1 + 1}\right\}\right) \geq \bar{R}_2. \tag{18}$$

From this, for a feasible allocation for Q_1 and Q_2, $\bar{Q}$ needs to satisfy the following:

$$\bar{Q} \geq \frac{2^{\bar{R}_2} - 1}{\nu}. \tag{19}$$

With a $\bar{R}_2$ satisfying (19), the maximization of the sum rate of RAMA can be formulated as

$$\begin{aligned} \max_{\omega, Q_1, Q_2} & \left\{ \log_2\left(1 + \alpha_1 \bar{P} + \beta Q_2\right) \right. \\ & \left. + \log_2\left(1 + \frac{\nu\omega Q_1}{\nu(1-\omega)Q_1 + 1}\right) \right\} \\ \text{subject to } & (18),\ 0 \leq \omega \leq 1, Q_1 + Q_2 \leq \bar{Q}. \end{aligned} \tag{20}$$

From the sum rate in (20), which is an increasing function of ω and the constraint in (18), we can find ω that depends on Q_1 as follows:

$$\omega(Q_1) = \frac{1}{2^{\bar{R}_2}}\left(1 - \frac{2^{\bar{R}_2} - 1}{\nu Q_1}\right). \tag{21}$$

Then, (20) reduces to

$$\begin{aligned} \max_{Q_1, Q_2} & \left\{ \log_2\left(1 + \alpha_1 \bar{P} + \beta Q_2\right) \right. \\ & \left. + \log_2\left(1 + \frac{\nu\omega(Q_1)Q_1}{\nu(1-\omega(Q_1))Q_1 + 1}\right) \right\} \\ \text{subject to } & Q_2 \geq \frac{2^{\bar{R}_2} - 1}{\beta},\ Q_1 + Q_2 \leq \bar{Q}. \end{aligned} \tag{22}$$

The optimal value of Q_1 (and Q_2) can be found by a one-dimensional search method.

IV. Numerical Results

In this section, we present numerical results of NOMA and RAMA under the assumption that

$$\alpha_1 = 1, \alpha_2 = \left(\frac{1}{d}\right)^\eta, \beta = \left(\frac{1}{d-1}\right)^\eta,$$

where d is the distance between the BS and user 2 and $\eta = 3$ is the path loss exponent (note that user 1 is located on the line connecting the BS and user 2 in this assumption, which might be favorable to RAMA). Furthermore, we assume that $\bar{R}_2 = \bar{U}_2$ in this section.

Fig. 3 (a) shows the sum rates of NOMA and RAMA for various values of $\bar{Q}$ when $\bar{P} = 20$ dB, $d = 2$, and $\bar{R}_2 = \bar{U}_2 = 1$. Note that if there is no feasible power allocation, the sum rate is set to 0. We can see that RAMA can have a feasible solution with a lower value of $\bar{Q}$. On the other hand, in NOMA, a higher value of $\bar{Q}$ is required for a feasible solution. This difference results from the uplink transmission of user 2 in NOMA. Since user 2 has to have a higher transmission power than user 1 in uplink transmissions, with a low total power of users, $\bar{Q}$, NOMA may not be able to find a feasible solution to guarantee $U_2 \geq \bar{U}_2 = 1$. On the other hand, in RAMA, since user 1 helps user 2 as a relay node, with a lower $\bar{Q}$, it can guarantee $U_2 \geq \bar{U}_2 = 1$. With a sufficiently large $\bar{Q}$, we can see that NOMA can have a higher sum rate than RAMA. In particular, as shown in Fig. 3 (b), NOMA can have a much higher U_1 than RAMA for a sufficiently large $\bar{Q}$. In NOMA, once the uplink transmission power for user 2, Q_2, is allocated to meet the required minimum rate of $U_2 = \bar{U}_2$, the rest of the power, $\bar{Q} - Q_2$, is allocated to user 1. Thus, U_1 increases with $\bar{Q}$ in NOMA for a sufficiently large $\bar{Q}$, which results in a higher sum rate.

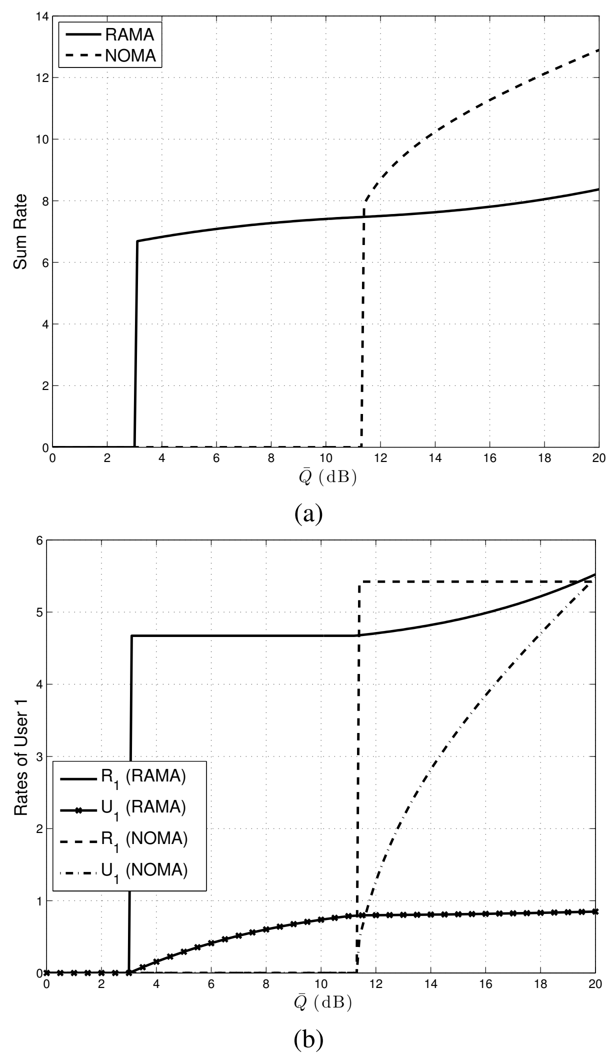

Fig. 3. Performances of NOMA and RAMA for various values of $\bar{Q}$ when $\bar{P} = 20$ dB, $d = 2$, and $\bar{R}_2 = \bar{U}_2 = 1$ (bps/Hz): (a) sum rates; (b) rates of user 1.

In Fig. 4 (a), we show the sum rates of NOMA and RAMA for different required minimum rates of uplink and downlink for user 2 when $\bar{P} = \bar{Q} = 10$ dB and $d = 2$. NOMA can provide a higher sum rate than RAMA when $\bar{R}_2$ is low. However, for a higher $\bar{R}_2$, NOMA cannot find a feasible solution. On the other hand, RAMA can find a feasible solution for a higher $\bar{R}_2$ by taking advantage of the role of user 1 as a relay node for user 2. In Fig. 4 (b), it is shown that R_1 and U_1 gradually decrease as $\bar{R}_2$ increases in RAMA.

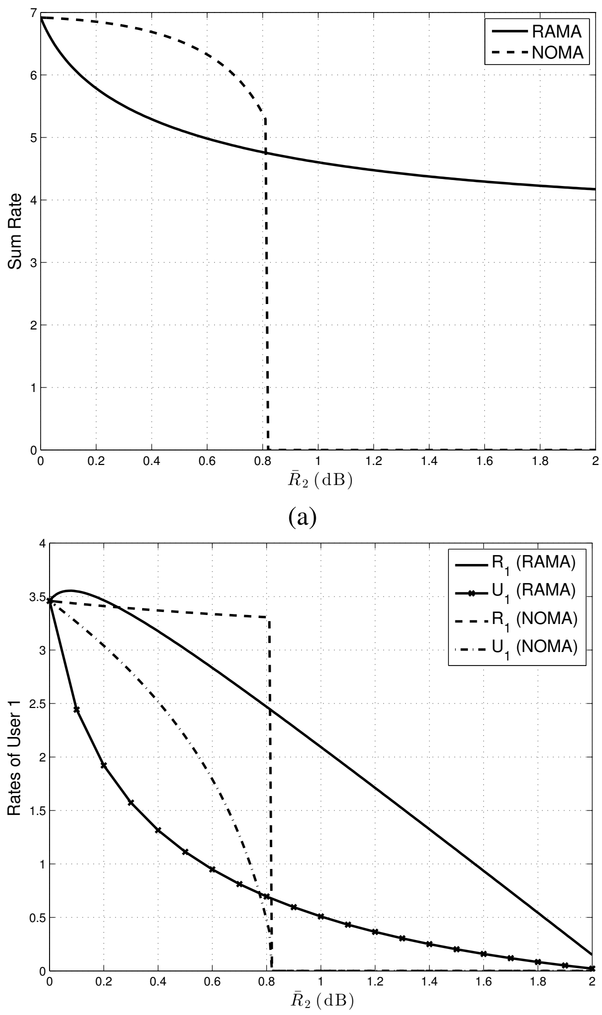

Fig. 4. Performances of NOMA and RAMA for various values of $\bar{R}_2 = \bar{U}_2$ when $\bar{P} = \bar{Q} = 10$ dB and $d = 2$: (a) sum rates; (b) rates of user 1.

Fig. 5 shows the sum rates of NOMA and RAMA for various values of d when $\bar{P} = \bar{Q} = 20$ dB and $\bar{R}_2 = \bar{U}_2 = 1$. In general, we can see that NOMA can provide a higher sum rate than RAMA unless d is small. If d is sufficiently small (i.e., user 2 is closely located to user 1), NOMA cannot effectively exploit the power difference for superposition coding. In this case, RAMA can perform better than NOMA.

V. Concluding Remarks

We studied two different multiple access schemes (NOMA and RAMA) that can increase the spectral efficiency by supporting two users in the same radio resource block. To see their performances, we considered the maximization of sum rate under transmission power constraints. In most cases, we found that NOMA can provide a higher sum rate than RAMA. However, RAMA was able to find a feasible solution for the power allocation under a wider range of conditions than NOMA. Consequently, by choosing one of them performing better than the other for given conditions, we could enjoy a degree of freedom to improve the spectral efficiency.

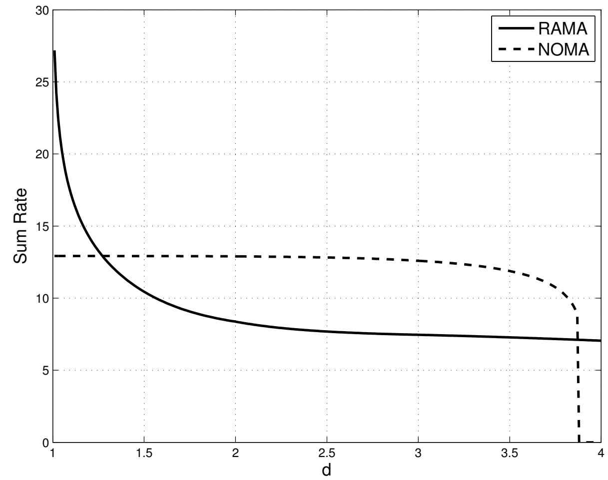

Fig. 5. Sum rates of NOMA and RAMA for various values of d when $\bar{P} = \bar{Q} = 20$ dB and $\bar{R}_2 = \bar{U}_2 = 1$.

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