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Energy Harvesting Non-Orthogonal Multiple Access System With Multi-Antenna Relay and Base Station

MATEEN ASHRAF[1], ADNAN SHAHID[2], (Senior Member, IEEE), JU WOOK JANG[3], AND KYUNG-GEUN LEE[1]
[1]Sejong University, Seoul 05006, South Korea
[2]Ghent University, 9000 Gent, Belgium
[3]Sogang University, Seoul 04107, South Korea

Corresponding author: Kyung-Geun Lee (kglee@sejong.ac.kr)

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ABSTRACT In this paper, we consider downlink non-orthogonal multiple access cooperative communication system. The base station (BS) serves two types of users, which are named relay user (RU) and far user (FU). The BS and RU are equipped with multiple transmit antennas. The RU harvests energy from the BS transmissions to perform the relaying operation for the FU. We have considered 1) amplify-forward; 2) decode-forward; and 3) quantize-map-forward relaying protocols at the RU. As the BS and RU have multiple antennas, therefore we consider 1) beamforming and 2) random antenna selection strategies at the BS and RU. Closed form expressions for the outage probability are provided for the aforementioned relay protocols and antenna strategies. Further, we show that for certain data rate range of the relay and FU the quantize-map-forward relaying protocol can perform better than the other two relaying protocols.

INDEX TERMS Cooperative communication, multiple input single output, non-orthogonal multiple access, outage probability, power splitting, RF energy harvesting.

I. INTRODUCTION

Wireless spectrum is one of the most precious resource of communication technology. Therefore, non-orthogonal multiple access (NOMA) is used to enhance the utilization of wireless spectrum in 5G networks. In NOMA, a single frequency spectrum is used to transmit the information from the BS to multiple destinations. Hence, the spectral efficiency of the NOMA systems is higher than the OMA systems. Considering a two destination scenario, it is widely accepted that the user that is farther from the BS experiences a bad channel as compared to the user that is located near the BS. In order to improve the performance of the FU it is possible to use the near user as a relay for the FU. Since the mobile users are battery powered therefore it is quite likely that the relaying operation cause exhaustion of the battery of the RU. This situation can be avoided if the RU harvests energy from BS transmissions to power its relaying operation. Although energy harvesting can prolong the battery life of the RU however it can have bad effects on the information exchange capability of the system. Therefore, it is important to study the performance of the cooperative NOMA systems with energy harvesting.

Much research effort has been carried out to study the performance of cooperative NOMA systems [1]–[6]. A cooperative NOMA scheme for 5G systems is presented in [1]. It is shown that considerable improvements in performance can be achieved due to cooperation between the users. A coordinated direct and relay transmission (CDRT) scheme is proposed in [2]. Their proposed scheme outperforms the non-CDRT scheme in terms of outage probability. In [3], a two stage relay selection scheme for cooperative NOMA is presented. The proposed two stage relay selection scheme is shown to be better than max-min selection scheme. Further, it is shown that the two stage scheme is also outage probability optimal. A full duplex cooperative NOMA system is proposed in [3]. Exact analytical expressions for outage probability and system capacity are derived in their work. It is shown that full duplex NOMA system can achieve lower outage probability and higher ergodic capacity under practical self-interference cancellation (SIC) conditions. All of the above works consider the decode and forward (DF) cooperation protocol for relaying purpose. Further, all the communicating entities are assumed to be equipped with single antenna in all of the above works. An amplify and forward (AF) relaying cooperative NOMA system is studied in [5]. Exact and lower bound expressions for outage probability are provided when BS and destinations are equipped with multiple antennas. All of the above works assume cooperative communication in the absence of direct link. However, in a practical system it is possible that a receiver receives signal from relay as well as from BS. Therefore, it is important to study the cooperative NOMA system in the presence of direct connection. In this context, Lv *et. al.* [6] have provided the performance results of cognitive radio NOMA (CRNOMA) while considering the direct connection in addition to the relay channel. The communication between a primary user and BS is assisted by multiple secondary users. It is shown that as the number of secondary users increase the performance of the CRNOMA improves significantly.

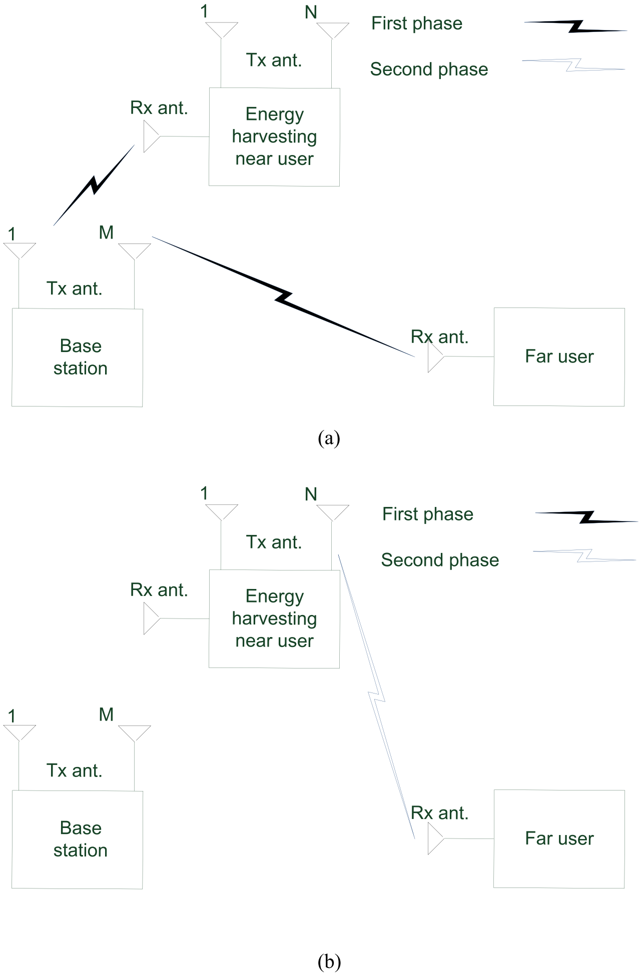
The study of cooperative NOMA with wireless energy harvesting is carried out in [7]–[9]. A cooperative NOMA system with two users and one energy harvesting decode-forward relay is studied in [7]. The outage probability expressions for two types of NOMA power allocation policies, namely NOMA with fixed power allocation and cognitive radio inspired NOMA, on the considered cooperative energy harvesting system are provided. This work is extended for multiple FUs and amplify-forward energy harvesting relay with multiple antennas in [8]. In [9], different near and FU selection strategies are proposed. In their work the selection of the users is based on the users location. DF protocol is used at the near user for forwarding the information to the FU. This work is extended in [10] for AF and DF protocol. Further, the user selection in [10] is based on the instantaneous channel state information instead of users location. The above works deal with the single antenna near and FUs. The study of multiple antenna source and near user is carried out in [11] and an optimal transceiver design for cooperative NOMA with energy harvesting is proposed. The source and near user are assumed to be equipped with multiple antennas and FU is assumed to have single antenna. Optimal transmit beamforming is proposed to maximize the signal to noise ratio of the FU.

In this paper we consider a downlink energy harvesting cooperative NOMA system. Our motivation for considering this system is explained below. We have considered NOMA since the capacity gains achieved from NOMA are better from orthogonal multiple access (OMA) if the ratio of the channel gains of spectrum sharing users is high [12], [13]. The performance improvement of NOMA as compared to OMA can be understood from following example. Suppose that there is a user close to the edge of its cell, denoted by U1, whose channel condition is very poor. For conventional multiple access, an orthogonal bandwidth channel, e.g., a time slot, will be allocated to this user, and the other users cannot use this time slot. The key idea of NOMA is to squeeze another user with a better channel condition, denoted by U2, into this time slot. Since U1's channel condition is very poor, the interference from U2 will not cause much performance degradation to U1, but the overall system throughput can be significantly improved since additional information can be delivered between the BS and U2. However, our work is different from the existing works in following ways. First, we consider multiple antenna BS and RU instead of considering single antenna BS and RU. This is done because the performance of multiple antenna system is much better than the single antenna systems thanks to increased degree of freedoms provided by multiple antennas. Second, the presence of direct connection between BS and FU. As cellular networks are becoming more dense the distance between the users and BS is decreasing. This results in increased probability of having a direct connection between BS and a user [14]. Therefore it is important to analyze the performance of the downlink systems in the presence of direct connection. Third, the consideration of energy harvesting at the RU. This is because the RU may not use its own energy for retransmitting the information to FU. By using the harvested energy in the first transmission phase the available transmit power at the RU is not a constant and it depends on the BS to RU channel. This dependence makes the analysis more complex with respect to the non-energy harvesting relay case. This is because the received signal at the FU in the second transmission phase is dependent on the channel state between BS to RU in addition to its dependence on the channel state between RU and FU. Fourth, consideration of quantize-map-forward (QMF) protocol for relaying in addition to the amplify-forward and decode-forward relay protocols. To the best of our knowledge no prior work consider all these possibilities in a single system model.

The paper is organized as follows. System model and related assumptions are described in Section 2. Section 3 presents the outage probability analysis of cooperative NOMA system with different relaying protocols. Simulation results are discussed in Section 4. Finally the conclusions of the paper are provided in Section 5.

II. SYSTEM MODEL

We consider a downlink communication system which consists of a BS and two users. One of the users is located near the BS at distance d_R while the other is located far from the BS at distance d_F ($d_F > d_R$). The distance between the near user and FU is denoted by d_{RF}. A pictorial representation of the system model is presented in Fig. 1. The BS uses nonorthogonal multiple access (NOMA) to serve both users. The user that is located near the BS also serve as a relay for the FU. Therefore, the near user is termed as RU. Although BS to FU communication is assisted by the RU however we assume that there exist a direct connection between BS and FU. The FU uses selection combining to combine the signals received from the BS and RU. The RU harvests energy from



(a)

(b)

FIGURE 1. (a) First transmission phase. The BS transmits composite signal (RU information and FU information) to RU and FU simultaneously. (b) Second transmission phase. RU transmits to FU.

the BS transmissions to power the retransmissions for FU. We assume power splitting protocol for energy harvesting at RU due to its simplicity. It is assumed that BS and RU use multiple transmit antennas while RU and SU use single antenna for reception. The BS allocates $0 < \alpha_1^2 \leq 1$ portion of its transmit power P_B to transmit the FU information while $0 < \alpha_2^2 \leq 1$ portion of P_B is used for RU information transmission. Therefore the transmitted composite signal from the BS is $\sqrt{P_B}\alpha_1 s_F + \sqrt{P_B}\alpha_2 s_R$ where s_R and s_F are the transmitted symbol from BS for RU and FU, respectively. The propagation between any two antennas is affected by small scale fading and path loss. The small scale fading between any two antennas is captured by independent Rayleigh distributed random variables. Therefore the channel gains between all the antennas are assumed to follow exponential distribution with parameter 1. The small scale channel gain between BS to RU (FU) is denoted by $|x|^2(|y|^2)$ while the small scale channel gain between RU to FU is denoted by $|z|^2$. We assume quasi static channels that remain stationary during one transmission time. The statistical properties of $|x|^2$, $|y|^2$ and $|z|^2$ depend on the particular antenna strategy used by BS and RU. In the following we discuss about the antenna strategies, energy harvesting protocol and relaying protocols.

A. ANTENNA STRATEGY

As BS (RU) has multiple antennas therefore the BS (RU) can use following strategies for antenna usage: (i) use beamforming for transmissions (ii) randomly select antenna for transmissions. The channel gains for beamforming strategy follow Gamma distribution. This point can be understood from following example. Let $\boldsymbol{h}$ denote the fading column vector (size of this vector depend on number of antennas at the transmitter) between the transmitter (BS or RU) and its desired/beamformed receiver (RU or FU). Each entity of $\boldsymbol{h}$ follows Rayleigh distribution as we have assumed above. Further assume that the information signal of the transmitter is denoted by s, for simplicity of exposition. Under the transmit beamforming, the transmitter will multiply the information signal with beamforming vector

$$b = \frac{\boldsymbol{h}^H}{||\boldsymbol{h}||}$$

before transmitting s. Therefore the transmitted signal will be the product of s and $\boldsymbol{b}$. This transmitted signal gets multiplied by the fading column vector h during its propagation through the channel. As a result the received signal at the receiver will be

$$s\frac{\boldsymbol{h}^H}{||\boldsymbol{h}||}\boldsymbol{h} + n$$

where n is the AWGN noise at the receiver with variance N_0. Therefore, the effective channel gain has become

$$\left|\frac{\boldsymbol{h}^H}{||\boldsymbol{h}||}\boldsymbol{h}\right|^2$$

which is the sum of exponential random variables and therefore we say that the channel gain for beamforming case becomes a Gamma random variable. The first strategy require channel state information at the transmitter.

B. POWER SPLITTING EH PROTOCOL

In this protocol the received signal at the relay is divided into two portions. One portion ρ $(0 < \rho \leq 1)$ is used for energy harvesting to power the relaying operation while the other portion $(1-\rho)$ is used for information processing. The energy harvesting efficiency is denoted as η in the rest of analysis.

C. RELAY PROTOCOL STRATEGY

The RU can use (i) AF (ii) DF or (iii) QMF protocol for relaying the information to the FU. The total transmission time is divided into two phases in all of the three protocols. In the first transmission phase the BS sends the composite signal to the RU and FU. In AF protocol the RU multiply its received signal with a variable gain before forwarding to FU. In DF protocol RU first decode the FU part from the received signal and then forward a new copy to the FU. On the other hand in QMF protocol the RU quantize the received signal and forward the quantized signal to the FU. It is widely accepted that the performance of QMF relaying protocol is better than AF and DF relaying protocols [15]–[17].

III. OUTAGE PROBABILITY ANALYSIS

In this section we provide the outage probability analysis of the three relaying protocols with different antenna strategies used by the relay and BS. The first three subsections provide the outage probability analysis for FU while the outage probability of the RU is provided in fourth subsection. By using the notation introduced in section II we can write the received signals during the first transmission phase at RU and FU as follows [10]

$$r_R = (\alpha_1 s_F + \alpha_2 s_R)\sqrt{P_B d_R^{-n}}x + n_R, \tag{1}$$

$$r_F = (\alpha_1 s_F + \alpha_2 s_R)\sqrt{P_B d_F^{-n}}y + n_F, \tag{2}$$

where n_r and n_F are the AWGN noises with same variances (N_0) at RU and FU, respectively. The SNR corresponding to the s_F signal at both receivers during the first transmission phase can be written as follows [10]

$$\gamma_R^1 = \frac{(1-\rho)\alpha_1^2\overline{\gamma}d_R^{-n}|x|^2}{(1-\rho)\alpha_2^2\overline{\gamma}d_R^{-n}|x|^2+1}, \tag{3}$$

$$\gamma_F^1 = \frac{\alpha_1^2\overline{\gamma}d_F^{-n}|y|^2}{\alpha_2^2\overline{\gamma}d_F^{-n}|y|^2+1}. \tag{4}$$

The random variables follow (i) a Gamma distribution (in case of beamforming) [18], [19] or (ii) they follow exponential distribution for other antenna strategies. The probability density function for both of the above cases can be written as follows

$$p_{g,beamforming}(g) = \frac{1}{(T-1)!}g^{T-1}e^{-g} \tag{5}$$

$$p_{g,exp}(g) = e^{-g} \tag{6}$$

where $g \in \{|x|^2, |y|^2, |z|^2\}$, $T \in \{M, N\}$. Corresponding to these pdf's the cumulative distribution functions (CDFs) are provided as follows

$$F_{g,beamforming}(g) = 1 - e^{-g}\sum_{k=0}^{T-1}\frac{g^k}{k!} \tag{7}$$

$$F_{g,exp}(g) = 1 - e^{-g} \tag{8}$$

In the following, we derive the outage probability expressions for AF, DF and QMF protocols with different antenna strategies used at the BS and RU.

A. AMPLIFY-FORWARD RELAYING OUTAGE PROBABILITY ANALYSIS

For AF relaying case we assume that the RU uses a variable gain AF protocol and the amplification gain is as follows

$$\Gamma = \frac{\rho\eta\overline{\gamma}|x|^2 d_R^{-n}}{\overline{\gamma}|x|^2 d_R^{-n}+1}. \tag{9}$$

The SNR expression for the FU during the second phase in the case of AF relaying can be written as (10), shown at the bottom of this page.

As we have assumed selection combining at the FU therefore the outage probability at the FU due to AF relaying for a given rate R can be written as follows

$$P_{o,FU,AF} = Pr\left(max(\gamma_F^1, \gamma_F^2) < 2^{2R}-1\right). \tag{11}$$

Using (4) and (10) the outage probability can be written as [10]

$$P_{o,FU,AF} = Pr\left(|y|^2 < \frac{\mathbb{R}}{\alpha_1^2\overline{\gamma}d_F^{-n} - \alpha_2^2\overline{\gamma}d_F^{-n}\mathbb{R}}\right)\Omega \tag{12}$$

where $\mathbb{R} = 2^{2R}-1$ and Ω is given as

$$\begin{aligned}\Omega = &\int_0^{\frac{\mathbb{R}}{\alpha_1^2\overline{\gamma}d_F^{-n}-\alpha_2^2\overline{\gamma}d_F^{-n}\mathbb{R}}} p_{|x|^2}(|x|^2)d|x|^2 \\ &+\int_{\frac{\mathbb{R}}{d_F^{-n}\overline{\gamma}(\alpha_1^2-\alpha_2^2\mathbb{R})}}^{\infty} Pr\left(z < \frac{\xi}{[\overline{\gamma}d_F^{-n}(\alpha_1^2-\alpha_2^2\mathbb{R})|x|^2-\mathbb{R}]}\right) \\ &\times p_{|x|^2}(|x|^2)d|x|^2,\end{aligned} \tag{13}$$

where $\xi = \frac{\mathbb{R}}{\rho\eta}$. It can be easily observed that if $\mathbb{R} \geq \frac{\alpha_1^2}{\alpha_2^2}$ then $P_{o,FU,AF} = 1$. Now we consider different possibilities for antenna usage.

1) BEAMFORMING AT BS AND RU

First we consider the possibility when BS use transmit beamforming for RU and RU use transmit beamforming for FU. We will denote the outage probability for this case as $P_{o,FU,AF}^{BFR,BF}$. With this antenna strategy both $|x|^2$ and $|z|^2$ follow Gamma distribution [18], [19] and the CDF is provided in (7) with $T = M$ and $T = N$ respectively. On the other hand $|y|^2$ follows exponential distribution with parameter 1. Now we can solve (12) for outage probability as follows

$$\begin{aligned}&P_{o,FU,AF}^{BFR,BF} \\ &= \left[1-e^{-\frac{\mathbb{R}}{\epsilon}}\right]\underbrace{\left[1-\int_{\frac{\mathbb{R}}{\epsilon}}^{\infty}\frac{(|x|^2)^{M-1}e^{-|x|^2}}{(M-1)!}e^{-\Theta}\sum_{k=0}^{N-1}\frac{\Theta^k}{k!}d|x|^2\right]}_{J_1},\end{aligned} \tag{14}$$

$$\gamma_F^2 = \frac{(\rho-\rho^2)\eta\overline{\gamma}^2\alpha_1^2|x|^4|z|^2 d_R^{-2n}d_{RF}^{-n}}{d_R^{-n}|x|^2[(\rho-\rho^2)\eta\overline{\gamma}^2\alpha_2^2|x|^2|z|^2 d_R^{-n}d_{RF}^{-n} + \rho\eta\overline{\gamma}|z|^2 d_{RF}^{-n} + \overline{\gamma}] + 1} \tag{10}$$

where $\Theta = \frac{\xi}{[\epsilon|x|^2-\mathbb{R}]}$ and $\epsilon = (\alpha_1^2\overline{\gamma}d_F^{-n} - \alpha_2^2\overline{\gamma}d_F^{-n}\mathbb{R})$. After substituting $u = ((\alpha_1^2\overline{\gamma}d_F^{-n} - \alpha_2^2\overline{\gamma}d_F^{-n}\mathbb{R})|x|^2 - \mathbb{R})$ we can simplify J_1 as follows

$$\begin{aligned}J_1 &= 1 - \sum_{k=0}^{N-1} \frac{1}{(k!)(M-1)!}\xi^k \frac{1}{\epsilon^M} \\ &\quad \times e^{-\frac{\mathbb{R}}{\epsilon}} \sum_{m=0}^{M-1} \binom{M-1}{m} \mathbb{R}^m \int_0^\infty e^{-\frac{\xi}{u}-\frac{u}{\epsilon}} u^{M-1-m-k} du.\end{aligned} \tag{15}$$

Now using [Eq. 3.471.9, 20] the above integration can be written as follows

$$\begin{aligned}J_1 &= 1 - \sum_{k=0}^{N-1} \frac{1}{(k!)(M-1)!}\xi^k \frac{1}{\epsilon^M} \\ &\quad \times e^{-\frac{\mathbb{R}}{\epsilon}} \sum_{m=0}^{M-1} \binom{M-1}{m} \mathbb{R}^m 2\,(\xi\epsilon)^{\frac{M-m-k}{2}} \\ &\quad \times K_{M-m-k}\left(2\sqrt{\frac{\xi}{\epsilon}}\right),\end{aligned} \tag{16}$$

where $K_v(.)$ is the vth order modified Bessel function of the second kind. Putting the value of J_1 in (16) into (14) we can find the outage probability for AF case when BS uses transmit beamforming for RU and RU uses transmit beamforming for FU.

Now we consider the other possibility when BS uses transmit beamforming for FU and RU also uses transmit beamforming for FU. We will denote the outage probability with $P_{o,FU,AF}^{BFF,BF}$. In this case $|y|^2$ and $|z|^2$ follow Gamma distribution while $|x|^2$ follows exponential distribution. After some mathematical manipulations it can be easily shown that

$$\begin{aligned}P_{o,FU,AF}^{BFF,BF} &= \left[1 - e^{-\frac{\mathbb{R}}{\epsilon}} \sum_{k=0}^{M-1} \frac{\mathbb{R}^k}{\epsilon^k k!}\right]\left[1 - \sum_{k=0}^{N-1} \frac{1}{k!}\xi^k \frac{1}{\epsilon}\right. \\ &\quad \left. \times\, e^{-\frac{\mathbb{R}}{\epsilon}} 2\,(\xi\epsilon)^{\frac{1-k}{2}}\, K_{1-k}\left(2\sqrt{\frac{\xi}{\epsilon}}\right)\right].\end{aligned} \tag{17}$$

2) RANDOM ANTENNA SELECTION AT BS AND RU

In this case $|x|^2$, $|y|^2$ and $|z|^2$ all follow exponential distributions with parameter 1. Therefore, the outage probability in (12) for this case can be written as follows

$$P_{o,FU,AF}^{R,R} = \left[1 - e^{-\frac{\mathbb{R}}{\epsilon}}\right]\left[1 - \frac{1}{\epsilon} e^{-\frac{\mathbb{R}}{\epsilon}} 2\,(\xi\epsilon)^{\frac{1}{2}}\, K_1\left(2\sqrt{\frac{\xi}{\epsilon}}\right)\right]. \tag{18}$$

B. DECODE-FORWARD RELAYING OUTAGE PROBABILITY ANALYSIS

In this case the RU first decode the FU signal (s_F) and then forwards it to FU. The transmit power for forwarding is equal to $\rho\eta P_B|x|^2 d_R^{-n}$ [10]. The outage probability in this case can be written as follows

$$\begin{aligned}P_{o,FU,DF} &= \underbrace{Pr\left(\max\{\gamma_R^1, \gamma_F^1\} < \mathbb{R}\right)}_{J_2} \\ &\quad + \underbrace{Pr\left(\gamma_R^1 > \mathbb{R}, \max\{\gamma_F^1, \rho\eta\overline{\gamma}|x|^2|z|^2 d_R^{-n} d_{RF}^{-n}\} < \mathbb{R}\right)}_{J_3}.\end{aligned} \tag{19}$$

As γ_R^1 and γ_F^1 are independent therefore we can write

$$J_2 = Pr\left(|y|^2 < \frac{\mathbb{R}}{\epsilon}\right) Pr\left(|x|^2 < \frac{\mathbb{R}}{\epsilon_2}\right), \tag{20}$$

where $\epsilon_2 = (1-\rho)d_R^{-n}\left(\alpha_1^2\overline{\gamma} - \alpha_2^2\overline{\gamma}\mathbb{R}\right)$. The value of J_3 for $\mathbb{R} < \frac{\alpha_1^2}{\alpha_2^2}$ case can be written as

$$J_3 = \int_{\frac{\mathbb{R}}{\epsilon}}^{\infty} F_{|z|^2}\left(\frac{\xi}{\overline{\gamma}|x|^2 d_R^{-n} d_{RF}^{-n}}\right) p_{|x|^2}(|x|^2) d|x|^2. \tag{21}$$

On the other hand if $\mathbb{R} \geq \frac{\alpha_1^2}{\alpha_2^2}$ then $J_3 = 0$ and $J_2 = 1$. Now we find the outage probability for different antenna strategies.

1) BEAMFORMING AT BS AND RU

First we assume that BS use beamforming for RU and RU use beamforming for FU. As discussed above, in this case both $|x|^2$ and $|z|^2$ follow Gamma distribution and the CDF is provided in (7) with $T = M$ and $T = N$ respectively. On the other hand $|y|^2$ follows exponential distribution with parameter 1. Therefore, J_2 can be written as

$$J_2 = \left(1 - e^{-\frac{\mathbb{R}}{\epsilon}}\right)\left(1 - e^{-\frac{\mathbb{R}}{\epsilon_2}} \sum_{k=0}^{M-1} \frac{\mathbb{R}^k}{\epsilon_2^k k!}\right). \tag{22}$$

Using $t = |x|^2$, J_3 can be written as follows

$$\begin{aligned}J_3 &= \left(1 - e^{-\frac{\mathbb{R}}{\epsilon}}\right) \int_{\frac{\mathbb{R}}{\epsilon_2}}^{\infty} \left(1 - e^{-\frac{\xi}{\overline{\gamma} t d_R^{-n} d_{RF}^{-n}}}\right. \\ &\quad \left. \times \sum_{k=0}^{N-1} \frac{1}{k!}\left(\frac{\xi}{\overline{\gamma} t d_R^{-n} d_{RF}^{-n}}\right)^k\right) \frac{1}{(M-1)!}(t)^{M-1} e^{-t} dt\end{aligned} \tag{23}$$

$$J_3 = \left(1 - e^{-\frac{\mathbb{R}}{\epsilon}}\right)\left[e^{-\frac{\mathbb{R}}{\epsilon_2}} \sum_{k=0}^{M-1} \frac{\mathbb{R}^k}{\epsilon_2^k k!} - \sum_{k=0}^{N-1} \frac{1}{(M-1)!k!} J_{3,k}\right] \tag{24}$$

where

$$J_{3,k} = \int_{\frac{\mathbb{R}}{\epsilon}}^{\infty} e^{-\frac{\xi}{\overline{\gamma} t d_R^{-n} d_{RF}^{-n}}} \left(\frac{\xi}{\overline{\gamma} t d_R^{-n} d_{RF}^{-n}}\right)^k t^{M-1} e^{-t} dt. \tag{25}$$

To the best of our knowledge $J_{3,k}$ cannot be solved in closed form. Therefore, we use high SNR approximation ($\overline{\gamma} \to \infty$) to solve $J_{3,k}$. With this assumption $e^{-\frac{\xi}{\overline{\gamma} t d_R^{-n} d_{RF}^{-n}}}$ can be replaced with $1 - \frac{\xi}{\overline{\gamma} t d_R^{-n} d_{RF}^{-n}}$ and $J_{3,k}$ becomes

$$J_{3,k} = \left(\frac{\xi}{\overline{\gamma} d_R^{-n} d_{RF}^{-n}}\right)^k \int_{\frac{\mathbb{R}}{\epsilon}}^{\infty} t^{M-k-1} e^{-t}\left[1 - \left(\frac{\xi t^{-1}}{\overline{\gamma} d_R^{-n} d_{RF}^{-n}}\right)\right] dt \tag{26}$$

Now $J_{3,k}$ can be easily solved in closed form by noting that [16]

$$\int_c^{\infty} t^l e^{-t} dt = \begin{cases} c^{\frac{l}{2}} e^{-\frac{c}{2}} W_{\frac{l}{2}, \frac{1+l}{2}}(c), & \text{if } l < 0 \\ \Gamma(l+1, c), & \text{if } l > 0 \\ e^{-c}, & \text{if } l = 0 \end{cases} \tag{27}$$

where $W_{m,n}(g)$ is the Whittaker function and $\Gamma(m, n)$ is the incomplete gamma function. Putting the values of J_2 and J_3 from (22) and (23) into (19) we can find the outage probability for the case when BS use beamforming for RU and RU use beamforming for FU.

Now we find the outage probability for the case when BS uses transmit beamforming for FU and RU also use beamforming for FU. As noted above, $|y|^2$ and $|z|^2$ will follow Gamma distribution while $|x|^2$ will follow exponential distribution. With these considerations, the value of J_2 in (19) will be

$$J_2 = \left(1 - e^{-\frac{\mathbb{R}}{\epsilon}} \sum_{k=0}^{M-1} \frac{\mathbb{R}^k}{\epsilon^k k!}\right)\left(1 - e^{-\frac{\mathbb{R}}{\epsilon_2}}\right). \tag{28}$$

On the other hand J_3 can be obtained by putting $M = 1$ in (24). The total outage probability will be the sum of J_2 and J_3.

2) RANDOM ANTENNA SELECTION AT BS AND RU

In this case J_2 in (22) is obtained by putting $M = 1$ and J_3 is obtained by putting $N = 1$ and $M = 1$ in (23). After that the values of J_2 and J_3 can be putted in (19) to obtain the outage probability. The final expression for outage probability can be written as

$$P^{R,R}_{o,FU,DF} = \left(1 - e^{-\frac{\mathbb{R}}{\epsilon}}\right)\left(1 - e^{-\frac{\mathbb{R}}{\epsilon_2}} + \frac{\xi}{\overline{\gamma} d_R^{-n} d_{RF}^{-n}} \left(\frac{\mathbb{R}}{\epsilon_2}\right)^{-\frac{1}{2}} \times e^{-\frac{\mathbb{R}}{2\epsilon_2}} W_{-\frac{1}{2}, \frac{1}{2}}\left(\frac{\mathbb{R}}{\epsilon_2}\right)\right) \tag{29}$$

C. QUANTIZE-MAP-FORWARD RELAYING OUTAGE PROBABILITY ANALYSIS

In QMF relaying the RU first decodes its own information (s_R). After that the decoded signal is subtracted from the received signal. The remaining signal is sum of the FU signal part and gaussian noise. This remaining signal is quantize-map-forwarded to the FU. In this case if the RU is unable to decode its signal then nothing is forwarded to the FU. Therefore, the outage event at FU can occur due to following two reasons: (i) RU is unable to detect its own signal and FU is unable to decode its signal from the BS direct connection, (ii) RU is able to decode its signal but FU is unable to decode its signal from the relayed signal and direct signal from the BS. It is to be noted that the relaying operation will be performed by the relay only when it is able to decode its own signal (s_R) and subsequently remove its effect through SIC from the received signal during the first transmission phase. On the other hand if the relay is unable to decode its own information during the first phase than no forwarding to FU will occur during the second transmission phase. Mathematically, the outage probability can be written as follows

$$P_{o,FU,QMF} = Pr\left(|x|^2 < \frac{\mathbb{R}_R}{\epsilon_R}, |y|^2 < \frac{\mathbb{R}}{\epsilon}\right) + Pr\left(|x|^2 > \frac{\mathbb{R}_R}{\epsilon_R}, |y|^2 < \frac{\mathbb{R}}{\epsilon}, \gamma_{QMF} < \mathbb{R}\right), \tag{30}$$

where $\mathbb{R}_R = 2^{R_R} - 1$, $\epsilon_R = (1-\rho) d_R^{-n} \left(\alpha_2^2 \overline{\gamma} - \alpha_1^2 \overline{\gamma} \mathbb{R}_R\right)$ and γ_{QMF} is the signal to noise ratio for quantize-map-forward relay link. In (30), the second term in both brackets represent the failure of direct link between BS and FU, first term in both brackets indicate the unsuccessful and successful decoding of the RU information at relay respectively while the third term in second bracket represents the failure of decoding at FU due to low signal to noise ratio of the relay link. The signal to noise ratio for quantize-map-forward relay link can be obtained by following the steps in [15]–[17]. The important steps in finding γ_{QMF} are presented in appendix and the final expression for γ_{QMF} is

$$\gamma_{QMF} \approx \frac{\eta\rho(1-\rho)\alpha_1^2 |x|^2 d_R^{-n} |z|^2 d_{RF}^{-n} \overline{\gamma}}{(1-\rho)\alpha_1^2 + \eta\rho d_{RF}^{-n} \overline{\gamma} |z|^2}. \tag{31}$$

Now we consider the outage probability for different antenna strategies at BS and RU.

1) BEAMFORMING AT BS AND RU

Assuming BS use transmit beamforming for RU and RU use transmit beamforming for FU the outage probability can be written as follows

$$P^{BFR,BF}_{o,FU,QMF} = \left(1 - e^{-\frac{\mathbb{R}}{\epsilon}}\right)\Bigg[\left(1 - e^{-\frac{\mathbb{R}_R}{\epsilon_R}} \sum_{k=0}^{M-1} \frac{\mathbb{R}_R^k}{\epsilon_R^k k!}\right) \underbrace{+ \int_{\frac{\mathbb{R}_R}{\epsilon_R}}^{\infty} Pr\left(|z|^2 < \frac{\xi\,(1-\rho)\alpha_1^2}{\overline{\gamma} d_{RF}^{-n}[(1-\rho)\alpha_1^2 |x|^2 d_R^{-n} - \mathbb{R}]}\right) p_{|x|^2}(|x|^2) d|x|^2 \Bigg].}_{J_4} \tag{32}$$

The value of J_4 depends on $\mathbb{R}$. First we consider the case when $\mathbb{R} < \frac{\mathbb{R}_R}{\epsilon_R}(1-\rho)\alpha_1^2 d_R^{-n}$. Using the CDF of $|z|^2$ and PDF of $t = |x|^2$ we can write J_4 as follows

$$J_4 = \int_{\frac{\mathbb{R}_R}{\epsilon_R}}^{\infty} \Bigg[1 - e^{-\frac{\xi\,(1-\rho)\alpha_1^2}{\overline{\gamma} d_{RF}^{-n}((1-\rho)\alpha_1^2 t d_R^{-n} - \mathbb{R})}} \times \sum_{k=0}^{N-1} \frac{1}{k!} \left(\frac{\xi\,(1-\rho)\alpha_1^2}{\overline{\gamma} d_{RF}^{-n}(t(1-\rho)\alpha_1^2 d_R^{-n} - \mathbb{R})}\right)^k \Bigg] \times \frac{1}{(M-1)!} t^{M-1} e^{-t} dt. \tag{33}$$

To the best of our knowledge the above integral can not be solved in closed form. Therefore, we use the approximation $\lim_{g \to 0} e^{-g} \simeq 1 - g$. After some algebraic manipulations J_4

can be simplified as follows

$$J_4 = \sum_{p=2}^{N-1} J_{4,p} + J_{4,N}, \tag{34}$$

where

$$\begin{aligned} J_{4,N} &= \frac{[\xi\ (1-\rho)\alpha_1^2]^N}{(N-1)!(M-1)!(\overline{\gamma} d_{RF}^{-n})^N} \int_{\frac{\mathbb{R}_R}{\epsilon_R}}^{\infty} \\ &\quad \times \left(\frac{1}{(t d_R^{-n}(1-\rho)\alpha_1^2 - \mathbb{R})}\right)^N \times t^{M-1}e^{-t}dt, \\ J_{4,p} &= \frac{[\xi\ (1-\rho)\alpha_1^2]^p}{(M-1)!(\overline{\gamma} d_{RF}^{-n})^p} \left(\frac{1}{(p-1)!} - \frac{1}{p!}\right) \\ &\quad \times \int_{\frac{\mathbb{R}_R}{\epsilon_R}}^{\infty} \left(\frac{1}{(t d_R^{-n}(1-\rho)\alpha_1^2 - \mathbb{R})}\right)^p \times t^{M-1}e^{-t}dt. \end{aligned}$$

After some algebraic manipulations the integral $\int_{\frac{\mathbb{R}_R}{\epsilon_R}}^{\infty}\left(\frac{1}{t d_R^{-n}(1-\rho)\alpha_1^2 - \mathbb{R}}\right)^v t^{M-1}e^{-t}dt$ can be written as follows

$$\begin{aligned} &\frac{e^{-\mathbb{R} d_R^{n}(1-\rho)^{-1}\alpha_1^{-2}}}{\left((1-\rho)\alpha_1^2 d_R^{-n}\right)^{M+v-1}} \sum_{m=0}^{M-1} \binom{M-1}{m} \mathbb{R}^{M-1-m}((1-\rho)\alpha_1^2 d_R^{-n})^m \\ &\qquad \times \int_{\frac{\mathbb{R}_R}{\epsilon_R} - \frac{\mathbb{R}}{(1-\rho)\alpha_1^2 d_R^{-n}}}^{\infty} u^{m-v}e^{-u}du, \end{aligned} \tag{35}$$

which can be further simplified with the help of (27). Putting (35) and (34) into (32) we can find the outage probability for $\mathbb{R} < \frac{\mathbb{R}_R}{\epsilon_R}(1-\rho)\alpha_1^2 d_R^{-n}$ case when BS use transmit beamforming for RU and RU use transmit beamforming for FU. On the other hand the outage probability for $\mathbb{R} > \frac{\mathbb{R}_R}{\epsilon_R}(1-\rho)\alpha_1^2 d_R^{-n}$ can be written as follows

$$\begin{aligned} &P_{o,Fu,QMF}^{BFR,BF} \\ &= \left(1 - e^{-\frac{\mathbb{R}}{\epsilon}}\right)\left[\left(1 - \sum_{k=0}^{M-1} \frac{\mathbb{R}^k e^{-\frac{\mathbb{R}}{(1-\rho)\alpha_1^2 d_R^{-n}}}}{((1-\rho)\alpha_1^2 d_R^{-n})^k k!}\right)\right. \\ &\quad + \int_{\frac{\mathbb{R}}{(1-\rho)\alpha_1^2 d_R^{-n}}}^{\infty} Pr\left(|z|^2 < \frac{\xi\ (1-\rho)\alpha_1^2}{\overline{\gamma} d_{RF}^{-n}(|x|^2(1-\rho)\alpha_1^2 d_R^{-n} - \mathbb{R})}\right) \\ &\qquad \left. \times p_{|x|^2}(|x|^2)d|x|^2 \right], \end{aligned} \tag{36}$$

which simplifies to

$$P_{out,QMF} = \left(1 - e^{-\frac{\mathbb{R}}{\epsilon}}\right)\left[1 - J_4^{'}\right], \tag{37}$$

where $J_4^{'}$ is given as

$$\begin{aligned} J_4^{'} &= \frac{1}{(M-1)!} \sum_{k=0}^{N-1} \frac{(\xi\ (1-\rho)\alpha_1^2)^k}{k!(\overline{\gamma} d_{RF}^{-n})^k} \\ &\quad \times \int_{\frac{\mathbb{R}}{(1-\rho)\alpha_1^2 d_R^{-n}}}^{\infty} e^{-\frac{\xi\ (1-\rho)\alpha_1^2}{\overline{\gamma} d_{RF}^{-n}((1-\rho)\alpha_1^2 t d_R^{-n} - \mathbb{R})}} \left(\frac{1}{(t(1-\rho)\alpha_1^2 d_R^{-n} - \mathbb{R})}\right)^k \\ &\qquad \times t^{M-1}e^{-t}dt. \end{aligned} \tag{38}$$

The above integral can be solved with the help of substitution and Binomial theorem. The final result is given below

$$\begin{aligned} P_{o,FU,QMF}^{BFR,BF} &= \left(1 - e^{\frac{\mathbb{R}}{\epsilon}}\right)\left[1 - \frac{e^{-\frac{\mathbb{R}}{(1-\rho)\alpha_1^2 d_R^{-n}}}}{(M-1)!\left[(1-\rho)\alpha_1^2 d_R^{-n}\right]^M}\right. \\ &\quad \times \sum_{k=0}^{N-1}\sum_{p=0}^{M-1} \frac{2\mathbb{R}^{M-p-1}\left(\mathbb{R}(1-\rho)\alpha_1^2\right)^k \left(\mathbb{R}(1-\rho)^2\alpha_1^4 d_R^{-n}\right)^{\frac{p-k+1}{2}}}{k!(\eta\rho\overline{\gamma} d_{RF}^{-n})^{\frac{k-1}{2}}} \\ &\qquad \left. \times K_{p-k+1}\left(2\sqrt{\frac{\xi}{\overline{\gamma} d_{RF}^{-n} d_R^{-n}}}\right)\right]. \end{aligned} \tag{39}$$

Now we consider the possibility where BS use transmit beamforming for FU and RU also use transmit beamforming for FU. Since $|y|^2$, $|z|^2$ follow Gamma distribution and $|x|^2$ follow exponential distribution therefore the outage probability for the case when $\mathbb{R} < \frac{\mathbb{R}_R}{\epsilon_R}(1-\rho)\alpha_1^2 d_R^{-n}$ can be written as follows

$$P_{o,FU,QMF}^{BFF,BF} = \left(1 - e^{-\frac{\mathbb{R}}{\epsilon}} \sum_{k=0}^{M-1} \frac{\mathbb{R}^k}{k!\epsilon^k}\right)\left[(1 - e^{-\frac{\mathbb{R}_R}{\epsilon_R}}) + J_4\right], \tag{40}$$

where J_4 can be obtained from (34) by putting $M = 1$. On the other hand if $\mathbb{R} > \frac{\mathbb{R}_R}{\epsilon_R}(1-\rho)\alpha_1^2 d_R^{-n}$ then the outage probability is

$$P_{o,FU,QMF}^{BFF,BF} = \left(1 - e^{-\frac{\mathbb{R}}{\epsilon}} \sum_{k=0}^{M-1} \frac{\mathbb{R}^k}{k!\epsilon^k}\right)\left[1 - J_4^{'}\right], \tag{41}$$

where $J_4^{'}$ can be obtained from (38) by putting $M = 1$.

2) RANDOM ANTENNA SELECTION AT BS AND RU

In this case all the channel gains follow exponential distribution and therefore the outage probability for $\mathbb{R} < \frac{\mathbb{R}_R}{\epsilon_R}(1-\rho)\alpha_1^2 d_R^{-n}$ can be written as follows

$$P_{o,FU,QMF}^{R,R} = \left(1 - e^{-\frac{\mathbb{R}}{\epsilon}}\right)\left[\left(1 - e^{-\frac{\mathbb{R}_R}{\epsilon_R}}\right) + J_4\right], \tag{42}$$

where J_4 can be obtained from (33) by putting $M = N = 1$. On the other the outage probability for $\mathbb{R} > \frac{\mathbb{R}_R}{\epsilon_R}(1-\rho)\alpha_1^2 d_R^{-n}$ can be written as follows

$$P_{o,FU,QMF}^{R,R} = \left(1 - e^{-\frac{\mathbb{R}}{\epsilon}}\right)\left[1 - J_4^{'}\right], \tag{43}$$

where $J_4^{'}$ can be obtained from (38) by putting $M = N = 1$.

Remark 1: It can be easily observed that the outage probability of the QMF case is better than the outage probability of AF and DF case when $\mathbb{R} \geq \frac{\alpha_1^2}{\alpha_2^2}$ and $\mathbb{R}_R < \frac{\alpha_2^2}{\alpha_1^2}$. This observation can be easily proved with the help of (32) as follows. For $\mathbb{R} > \frac{\alpha_1^2}{\alpha_2^2}$ the outage probability of the AF and DF case is 1. In similar way the first product in (32) is also 1. However, the second product in (32) will be equal to 1 only if $Pr\left(|z|^2 < \frac{\xi\ (1-\rho)\alpha_1^2}{\overline{\gamma} d_{RF}^{-n}[(1-\rho)\alpha_1^2|x|^2 d_R^{-n} - \mathbb{R}]}\right) = 1$ for all values of $|x|^2$. This can be true only if $[(1-\rho)\alpha_1^2|x|^2 d_R^{-n} - \mathbb{R}]$ is negative for all values of $|x|^2 > \frac{\mathbb{R}_R}{\epsilon_R}$ or if it is zero for all values of $|x|^2 > \frac{\mathbb{R}_R}{\epsilon_R}$. Both of these conditions can not be true therefore the second product in (32) is less than 1 and hence the outage probability for QMF case is smaller than the AF and DF case when $\mathbb{R} \geq \frac{\alpha_1^2}{\alpha_2^2}$ and $\mathbb{R}_R < \frac{\alpha_2^2}{\alpha_1^2}$.

Remark 2: Although we consider only beamforming and random antenna selection strategies. However, our analysis can be directly applied to the case when BS and RU are equipped with directional antennas. In this case the expressions for the PDF and CDF of channel gains will follow exponential distribution however the parameter of the exponential distribution will depend on the number of directive antennas at the transmitting end. The interested reader is referred to [section II, 21] for further details. For directive antennas, it is not necessary to have channel state information at the transmitter.

D. OUTAGE PROBABILITY OF RU

For AF and DF relaying protocols the RU first tries to decode the FU signal part and if the decoding is successful than RU use successive interference cancellation by subtracting the FU signal part and then performs the decoding of its own signal. After performing the SIC the remaining signal at RU can be written as follows

$$r_R^{'} = \sqrt{(1-\rho)P_B d_R^{-n}}\alpha_2 s_R x + n_R, \tag{44}$$

with corresponding signal to noise ratio $\gamma_R^R = (1-\rho)\alpha_2^2 d_R^{-n}\overline{\gamma}|x|^2$. Therefore, the general outage probability for RU in case of AF and DF can be written as follows

$$\begin{aligned} P_{out,RU}^{AF-DF} &= Pr\left(|x|^2 < \frac{\mathbb{R}}{\epsilon_2}\right) \\ &\quad + Pr\left(|x|^2 > \frac{\mathbb{R}}{\epsilon_2}, |x|^2 < \frac{\mathbb{R}_R}{(1-\rho)\alpha_2^2 d_R^{-n}\overline{\gamma}}\right). \end{aligned} \tag{45}$$

The above expression can be further simplified as follows

$$P_{out,RU}^{A-DF} = \begin{cases} F_{|x|^2}\left(\dfrac{\mathbb{R}_R}{(1-\rho)\alpha_2^2 d_R^{-n}\overline{\gamma}}\right), & \\ \qquad \mathbb{R}_R > \dfrac{\alpha_2^2\mathbb{R}}{(\alpha_1^2 - \alpha_2^2\mathbb{R})}, \mathbb{R} < \dfrac{\alpha_1^2}{\alpha_2^2} & \\ F_{|x|^2}\left(\dfrac{\mathbb{R}}{(1-\rho)d_R^{-n}\overline{\gamma}(\alpha_1^2 - \alpha_2^2\mathbb{R})}\right), & \\ \qquad \mathbb{R}_R < \dfrac{\alpha_2^2\mathbb{R}}{(\alpha_1^2 - \alpha_2^2\mathbb{R})}, \mathbb{R} < \dfrac{\alpha_1^2}{\alpha_2^2} & \\ 1, \qquad \mathbb{R} \geq \dfrac{\alpha_1^2}{\alpha_2^2} & \end{cases} \tag{46}$$

TABLE 1. Simulation parameters.

Parameter	Value	Parameter	Value
α_1^2	.7	α_2^2	.3
d_R	.5 m	d_F	1.5 m
d_{RF}	1 m	n	2
M	4	N	2
ρ	.7	η	1
$\mathbb{R}$	$\{1, 2\}$	$\mathbb{R}_R$	$\{.15, .35, 5, 10\}$

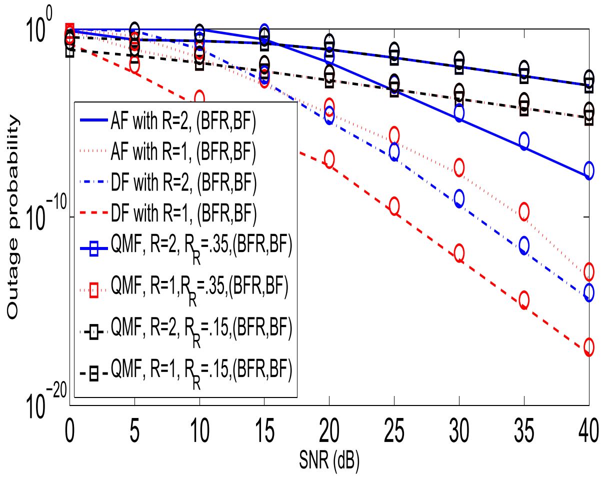


FIGURE 2. Outage probability for FU when BS use transmit beamforming for RU and RU use transmit beamforimg for FU. Simulation results are marked by circles.

where $F_{|x|^2}(|x|^2)$ can be obtained from (7) or (8) depending upon the antenna strategy used. On the other hand, in QMF the relay do not decode the FU signal part and hence no successive interference cancellation is performed. Therefore, the general expression for outage probability is as follows

$$P_{out,RU,QMF} = F_{|x|^2}\left(\frac{\mathbb{R}_R}{\epsilon_R}\right), \tag{47}$$

if $\mathbb{R}_R < \frac{\alpha_2^2}{\alpha_1^2}$ and 1 if $\mathbb{R}_R \geq \frac{\alpha_2^2}{\alpha_1^2}$. The value of $F_{|x|^2}$ can be obtained from (7) if the BS use beamforming for RU, whereas (8) is used for the case when BS use beamforming for FU.

IV. SIMULATION RESULTS

Simulations are performed in MATLAB to obtain the results. The important parameters for the simulations are provided in Table 1. In the following, we present six types of results. First three result present the outage probability for FU with different relaying protocols, the next two result present the outage probability for RU with different relaying protocols and the final result shows the dependence of outage probability on the power splitting ratio. Fig. 2 shows the outage probability of FU when the BS use transmit beamforming for RU and RU use transmit beamforming for FU (BFR, BF) for AF, DF and QMF relaying protocols. It can be observed that the DF outperforms the other two relaying protocols in high SNR regime. However, it can be observed that the QMF scheme is slightly better than the DF relaying protocol for relatively small SNRs. The improvement can be explained as follows. In the low SNR, RU cannot decode the FU signal part correctly and hence no forwarding occurs however with QMF since no detection is performed therefore the RU relays a

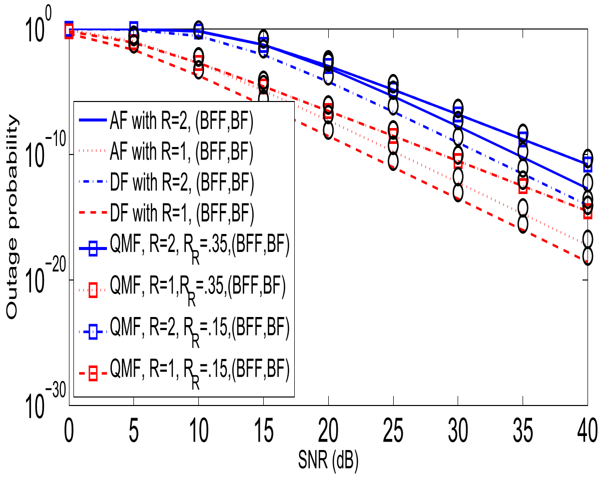


FIGURE 3. **Outage probability for FU when BS and RU use transmit beamforming for FU. Simulation results are marked by circles.**

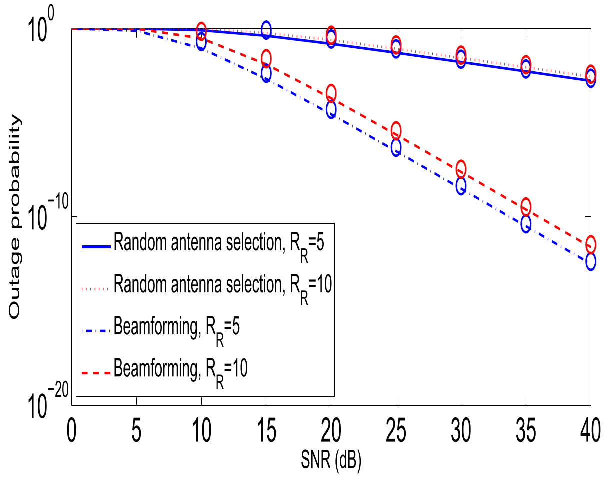


FIGURE 5. **Outage probability for RU with AF and DF relaying when $\mathbb{R} = 2$. Simulation results are marked by circles.**

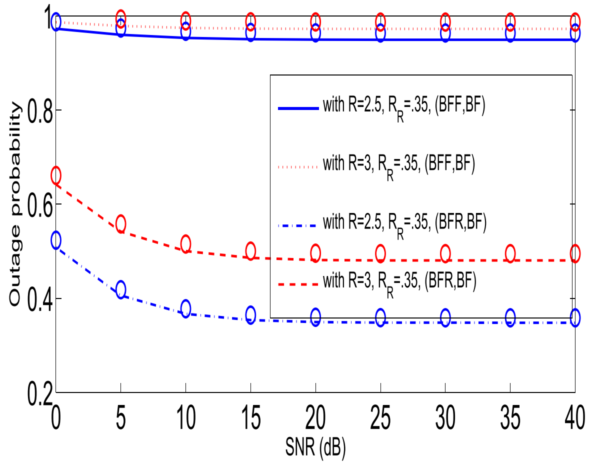


FIGURE 4. **Outage probability for FU with QMF and $\mathbb{R} > \frac{\alpha_1^2}{\alpha_2^2}$. Simulation results are marked by circles.**

quantized version of the FU signal. As a result the FU receive two copies and hence a reduction in outage probability. One other important observation is that the outage probability for QMF relaying does not vary by varying the value of $\mathbb{R}_R$ as long as it is less than $\frac{\alpha_2^2}{\alpha_1^2}$.

Fig. 3 shows the outage probability of FU when BS and RU use transmit beamforming for FU (BFF, BF). Comparing these results with the results of Fig. 2 we can observe that for low SNRs the (BFF, BF) scheme performs better than (BFR, BF) scheme. However, the opposite is true for the high SNR case. This is because the signal quality of the relayed signal is better at the FU for higher SNRs while it is not good for low SNR.

Now we show the outage probability for the FU when $\mathbb{R} > \frac{\alpha_1^2}{\alpha_2^2}$. As observed in Section III the outage probability for FU with DF and AF is 1 when $\mathbb{R} > \frac{\alpha_1^2}{\alpha_2^2}$. Therefore, we only show the outage probability for QMF relaying protocol. Fig. 4 shows the outage probability. It can be observed that the outage probability for (BFF, BF) scheme is much higher than the (BFR, BF) scheme. This is because the (BFF, BF) scheme enhances the direct link communication however this enhancement cannot make the outage probability < 1. On the other hand the (BFR, BF) scheme improves the BS to RU communication thus improving the chances of having a successful detection from the relay link.

Now we show the outage probability results for the RU. Fig. 5 shows the outage probability of the RU with AF and DF relaying protocol. The outage probability for beamforming case is much smaller than the random antenna selection. The outage probability for $\mathbb{R}_R < \frac{\alpha_2^2\mathbb{R}}{(\alpha_1^2-\alpha_2^2\mathbb{R})}$ is represented by curve for $\mathbb{R}_R = 5$ and it cannot be higher or smaller than this curve for $\mathbb{R}_R < \frac{\alpha_2^2\mathbb{R}}{(\alpha_1^2-\alpha_2^2\mathbb{R})}$. However, it becomes higher with the increase in $\mathbb{R}_R$ beyond $\frac{\alpha_2^2\mathbb{R}}{(\alpha_1^2-\alpha_2^2\mathbb{R})}$. The dependence on $\mathbb{R}$ is due to the successive interference cancellation at the RU of the s_F signal part.

The outage probability of RU with QMF relaying is shown in Fig. 6. The outage probability in this case is independent of $\mathbb{R}$ however it increases with the increase in $\mathbb{R}_R$. The outage probability for $\mathbb{R}_R > \frac{\alpha_2^2}{\alpha_1^2}$ is 1 and therefore we only show the outage probability for the case when $\mathbb{R}_R < \frac{\alpha_2^2}{\alpha_1^2}$.

Fig.7 and Fig. 8 show the dependence of outage probability on the power splitting ratio for different relaying protocols with (BFR, BF) and (BFF, BF) schemes respectively. For these results we have chosen $\mathbb{R} = 1$ and $\frac{P_B}{N_0} = 1000$. The outage probability for both schemes is a convex function of the power splitting ratio (ρ). The convexity for the AF and QMF relaying protocols can be explained as follows. From (10) and (31) we can see that for AF and QMF relaying protocols the received SNRs at the FU are concave functions of the ρ and since SNR has inverse relationship with the outage probability therefore we observe that outage probability is convex function of the ρ. The convexity of the DF relaying can be explained as follows. For very small values of ρ the available transmit power for the second transmission phase

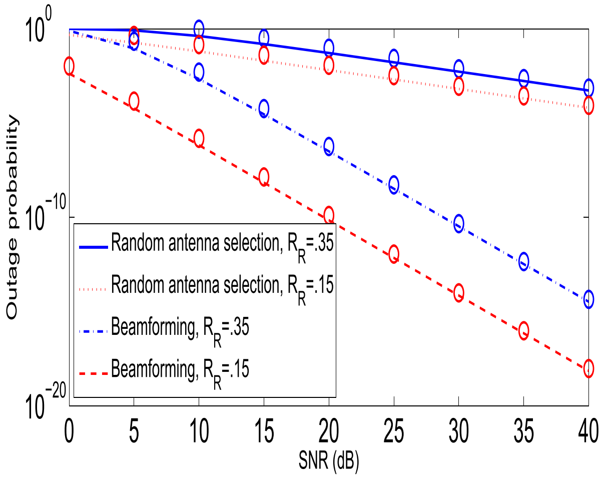


FIGURE 6. **Outage probability for RU with QMF relaying. Simulation results are marked by circles.**

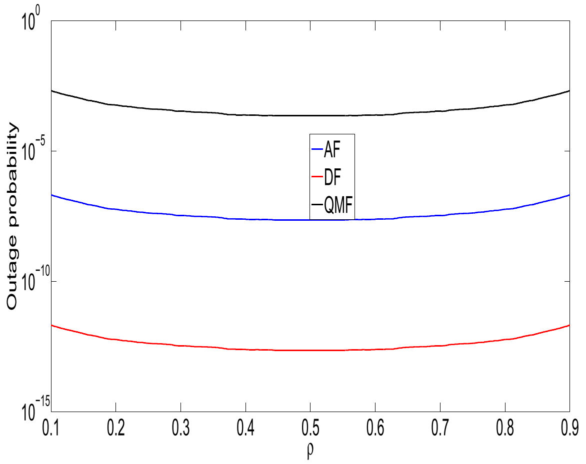


FIGURE 7. **Outage probability as a function of ρ for (BFR,BF) scheme.**

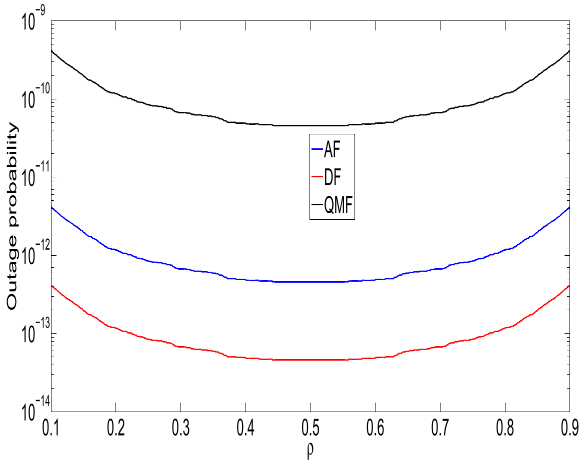


FIGURE 8. **Outage probability as a function of ρ for (BFF,BF) scheme.**

at the relay is small and hence this results in increase of the outage probability. On the other hand for higher values of ρ the signal fed to the information decoding circuitry at the relay user becomes week which increases the probability of no forwarding from the RU. This ultimately causes a rise in the outage probability.

V. CONCLUSIONS

In this paper we provide the closed form expressions for the outage probability of cooperative NOMA system with multiple antenna BS and relay. We consider three relaying protocols namely AF, DF and QMF. In addition, we study the usage of beamforming and random antenna selection at the BS and RU. The outage probability at the FU and RU depends on the data rate, antenna strategy and relaying protocol. The main observation of the article are summarized below.

- The outage probability of the FU is smallest for DF relaying protocol in the high SNR regime when $\mathbb{R} < \frac{\alpha_1^2}{\alpha_2^2}$.
- The outage probability of the FU for QMF relaying protocol is better than the DF relaying protocol in the low SNR regime when $\mathbb{R} < \frac{\alpha_1^2}{\alpha_2^2}$.
- The outage probability of the FU for QMF relaying protocol is smaller than the outage probability of the other relaying protocols when $\mathbb{R} \geq \frac{\alpha_1^2}{\alpha_2^2}$ and $\mathbb{R}_R < \frac{\alpha_2^2}{\alpha_1^2}$.
- The outage probability of the RU depends on $\mathbb{R}$ for AF and DF relaying protocol while it only depends on $\mathbb{R}_R$ for QMF relaying protocol.
- The transmit beamforming (BFR, BF) performs better than transmit beamforming (BFF, BF) in the low SNR regime while tranmsit beamforming (BFF, BF) performs better than transmit beamforming (BFR, BF) in the high SNR regime.

APPENDIX

STEPS FOR FINDING γ_{QMF}

The mutual information between BS and FU for the case of QMF relaying can be written as follows [Eq. 10, 17]

$$I = \log(1 + \gamma_{QMF}) = \log\left(1 + \frac{SNR_{BR}SNR_{RF}}{1 + SNR_{BR} + SNR_{RF}}\right) \tag{48}$$

where SNR_{BR} is the signal to noise ratio linked with the FU signal at the RU and SNR_{RF} is the signal to noise ratio of the relayed signal at the FU. Mathematically, they are written as follows

$$\begin{aligned} SNR_{BR} &= (1-\rho)\alpha_1^2\overline{\gamma}|x|^2 d_R^{-n}, \\ SNR_{RF} &= \eta\rho\overline{\gamma}|x|^2 d_R^{-n}|z|^2 d_{RF}^{-n} \end{aligned}$$

Assuming $SNR_{BR} + SNR_{RF} >> 1$, we can write $\gamma_{QMF} \simeq \frac{SNR_{BR}SNR_{RF}}{SNR_{BR}+SNR_{RF}}$ as in (31).

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MATEEN ASHRAF received the B. Eng. and M.S. degrees in 2010 and 2013, respectively. He is currently pursuing the Ph.D. degree with the Department of Information and Communication Engineering, Sejong University, South Korea.

ADNAN SHAHID (SM'17) received the B.Eng. and M.Eng. degrees in computer engineering with communication specialization from the University of Engineering and Technology, Taxila, Pakistan, in 2006 and 2010, respectively, and the Ph.D. degree in information and communication engineering from the Sejong University, South Korea, in 2015. From 2012 to 2015, he was a Ph.D. Research Assistant with Sejong University, South Korea. From 2007 to 2012, he served as a Lecturer with the Electrical Engineering Department, National University of Computer and Emerging Sciences, Pakistan. He is currently a Post-Doctoral Researcher with the ID Laboratory, Department of Information Technology, Ghent University–imec, Belgium. He is coordinating and actively involved in the research activities of the research project eWINE (https://ewine-project.eu/) funded by European Commission under the Horizon2020 program (Call: H2020-ICT-2015. Topic: ICT-12-2015). From 2015 to 2016, he was with the Department of Computer Engineering, Taif University, Saudi Arabia. In 2015, he was a Post-Doctoral Researcher with Yonsei University, South Korea.. He was also a recipient of the prestigious BK 21 plus Post-doctoral program at Yonsei University, South Korea. He is actively involved in various research activities. He is also serving as an Associate Editor of IEEE Access.

JU WOOK JANG received the B.S. degree in electronic engineering from Seoul National University, Seoul, South Korea, the M.S. degree in electrical engineering from the Korean Advanced Institute of Science and Technology, and the Ph.D. degree in electrical engineering from the University of Southern California, California, LA, USA. From 1985 to 1988 and from 1993 to 1994, he was with Samsung Electronics, Suwon, South Korea, where he was involved in the development of a 1.5-Mb/s video codec and a parallel computer. Since 1995, he has been with Sogang University, Seoul, South Korea, where he is currently a Professor. His current research interests include WiMAX protocols, mobile networks, and next-generation networks. He received the LG Yonam overseas research grant in 2001. He has also built systems for videoconferencing, streaming, home networks and *ad hoc* networks using protocols, such as RTP, SIP, Internet of Things, and Blockchain.

KYUNG-GEUN LEE received the B.S. and M.S. degrees in electronics engineering from Seoul National University and Korea Advanced Institute of Science and Technology in 1981 and 1983, respectively, the Ph.D. degree from the School of Electrical Engineering, Cornell University, Ithaca, NY, USA, in 1992. From 1983 to 1986 and from 1992 to 1998, he was a Principal Engineer with the Network Research Group, Samsung Electronics, South Korea. He is currently a Full Professor with the Department of Information and Communication Engineering, Sejong University. He was the Director of Computing and Information Center and also the Dean with the Electrical and Information Engineering College, Sejong University. His current research interests include wired and wireless networking, smart buildings and energy harvesting, cognitive radios, and network management.

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