Outage Performance Analysis for User Cooperative NOMA with Incremental Hybrid Forwarding Protocols

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Received: date / Accepted: date

Abstract Non-orthogonal multiple access (NOMA) collaborative communication is extremely beneficial to the users with poor channel conditions. It is essential to examine the performance of different NOMA users with superior cooperative forwarding protocols. This paper addresses the user cooperative NOMA system where one strong user (U2) assists one weak user (U1) to forward messages, and investigates the outage performance of both users with hybrid decode-and-amplify forwarding (HDAF) protocol. First, we derive the outage probability of U2 and U1 with HDAF. Secondly, we provide the closed-form expression for outage probability of U1 with the incremental hybrid decode-and-amplify forward (IHDAF) protocol at U2, which can further enhance the outage performance of U1 compared with HDAF. Moreover, we also present the system throughput expression and provide deep analysis on the effect of different forwarding protocols. Numerical results and Monte Carlo simulations jointly confirm the correctness of all the analytic derivations. In addition to saving the energy consumption of U2, IHDAF can make U1 achieve superior outage performance compared to HDAF. However, the system throughput almost overlap for both schemes given a threshold rate pair.

Keywords Non-orthogonal multiple access (NOMA) · Hybrid decode-and-amplify forwarding (HDAF) · Incremental hybrid decode-and-amplify forward (IHDAF) · Outage probability · System throughput

1 Introduction

From the first generation (1G) to 5G, mobile communication technology continuously experiences the revolutionary development towards faster data rate and higher bandwidth as well as greater connection almost every decade. Diverse interconnecting mobile terminals brings people more convenience in the information acquisition. Nowadays, faced with the connection demand for numerous mobile devices, non-orthogonal multiple access (NOMA) receives more and more attention as a promising scheme in 5G. NOMA technology realized in power domain is to allocate different power levels to different users according to users’ channel qualities. Moreover, successive interference cancellation (SIC) is applied to cancel the inter-user interference at the NOMA terminals [1]. To resolve the massive connection problem of mobile devices, only NOMA technology is far from meeting the requirements. It is also necessary for user cooperation with each other.

The relay plays an important role in the cooperative communication system. The relaying forwarding protocols have a great influence on the system performance. The decode-forward (DF) and amplify-forward (AF) are two types of commonly used ones [2]. Based on DF and AF, the selective relay and incremental relay forwarding protocols were proposed in [2] where incremental relay achieves higher outage performance than traditional relay schemes and selective relay. The hybrid decode-amplify-forward and coded cooperation (DAF-CC) protocol was proposed for the first time in [3], and research results show that DAF-CC is superior to traditional schemes. After that, the HDAF forwarding protocol [4] was proposed and further verified as a better scheme than traditional ones by analyzing symbol error probability (SEP). Reference [5] studied the HDAF scheme in the multi-relay cooperative communication system. In [6], the outage performance with HADF protocol is significantly improved compared with AF and DF. Reference [7] proposed IHDAF protocol for the first time, and demonstrated that the performance of IHDAF relay scheme is better than incrementalselective DF (ISDF) and incremental DF (Incremental DF).
relay schemes. In [2–7], they are traditional DF and AF relays. With the emergence of HDAF and IHDAF relays with superior performance, the scholars have conducted a lot of research work in this field [8–12]. In [8], the combination of HDAF and NOMA technology was proposed for the first time, where simulation results show that HDAF-NOMA can achieve larger sum channel capacity and system throughput compared with the traditional scheme. Based on [8], reference [9] proposed HDAF-NOMA with opportunistic layered multicast, and showed that the proposed scheme can achieve greater maximum transmission rate, system throughput and low latency compared to traditional multicast schemes. In [10], the performance analysis of symbol-error-rate (SER) was presented for multi-source and multi-target cooperative vehicle network under HDAF cooperative relay, which shows that HDAF can greatly reduce SER compared with AF and DF protocols. In [11], the outage performance of IHDAF in multi-relay cooperation system was studied, where numerical and simulation results verify that the outage performance of IHDAF protocol is better than ISDF and incremental AF (IAF). Reference [12] proposed an IHDAF collaboration scheme based on free space optical (FSO) communication system, which shows that the proposed IHDAF improves the system performance compared to other traditional collaborative FSO systems.

However, the references [2–12] have been studied for dedicated relay systems, and to achieve the large-scale mobile device interconnections, a large number of relay stations need to be constructed, which is undoubtedly expensive. Fortunately, the solution to this problem has already been obtained in [13, 14], which utilizes the user cooperation to improve the system throughput and cell coverage. In addition, the outage performance of HDAF-NOMA was investigated for the user cooperative system in [15].

In this paper, we investigate a user cooperation system based IHDAF relaying protocol, different from the HDAF scheme in [15] which employs selection combining (SC) approach at the weak user, while we consider a maximum ratio combing (MRC) at the weak user. The major contribution of this paper is as follows:

- We for the first time apply the IHDAF protocol into a user collaborative NOMA system to improve the outage performance of the weak user.
- We successively derive the closed-form outage expressions of the weak user under HDAF and IHDAF protocols combined with MRC, and further conduct an analysis on the system throughput.
- The numerical results verify that the closed-form derivations and Monte Carlo simulations are in complete agreement. Moreover, we provide a comparison with the HDAF protocol in [15] and validate the superiority of the IHDAF protocol.

The remainder of this article is arranged as follows. Section 2 is a presentation of the system model. Section 3 deduces the outage probability of U1 and U2 as well as the system throughput. Section 4 is the analysis and discussion on the simulation results. Section 5 is a conclusion of the paper.

### 2 System Model

As depicted in Fig.1, the considered user collaboration NOMA system is comprised of a base station (BS), a weak user (U1) and a strong user (U2). The strong user near the BS can also serve as a relay node to assist signal transmission of the weak user far away from the BS. The entire transmission process is divided into two time slots. In the first time slot, the BS sends signals $s(t)$ to U1 and U2 simultaneously. In the second time slot, U2 forwards U1’s message. Each node has a single antenna and the strong user operates in half-duplex mode.

The superimposed signal from BS can be expressed as

$$s(t) = \sqrt{\alpha_1 P_s} x_{1s}(t) + \sqrt{\alpha_2 P_s} x_{2s}(t)$$  \quad (1)$$

where $P_s$ is the BS transmit power. $\alpha_1$ and $\alpha_2$ are the allocated power coefficients, $x_{1s}(t)$ and $x_{2s}(t)$ are the transmitted information corresponding to U1 and U2, respectively. And $\alpha_1 + \alpha_2 = 1$. Assume that $E(|x_{1s}|^2) = 1$, $E(|x_{2s}|^2) = 1$.

In the first time slot, the base station broadcasts a superimposed signal to U1 and U2, then the signals received by U1 and U2, respectively, are written as

$$y_{1,1}(t) = h_{1s}(t)s(t) + n_{1,1}(t)$$  \quad (2)$$

$$y_{1,2}(t) = h_{2s}(t)s(t) + n_{1,2}(t)$$  \quad (3)$$

where $h_{1s}(t) \sim \text{CN}(0, \lambda_1)$, $h_{2s}(t) \sim \text{CN}(0, \lambda_2)$ denote the channel coefficients from BS to U1, BS to U2, respectively. Here $n_{1,1} \sim \text{CN}(0, \sigma^2)$ and $n_{1,2} \sim \text{CN}(0, \sigma^2)$ represent the additive gaussian white noise (AWGN) at U1 and U2, respectively. The notation CN $(0, \sigma^2)$ denotes the complex Gaussian distribution with the mean zero and the variance $\sigma^2$.

#### 2.1 DF Protocol

Assuming that the U1 message is successfully decoded at U2 using DF mode, the signal received at U1 in the second time slot can be expressed as

$$y_{2,1}^{DF}(t) = h_{12}(t) \sqrt{P_s} x_{1s}(t) + n_{2,1}(t)$$  \quad (4)$$

where $h_{12}(t) \sim \text{CN}(0, \lambda_2)$ is the channel coefficient from U2 to U1, and $n_{2,1} \sim \text{CN}(0, \sigma^2)$ is the AWGN at U1 during the second time slot, and $P_s$ is the transmission power to forward the U1 message by U2.
The signal received at U2 in the first time slot is first decoded by the SIC technique, its own message is finally decoded. Therefore, from (3), the signal-to-interference-plus-noise ratio (SINR) for decoding U1 at U2 can be expressed as

$$\gamma_{12}^{s_1} = \frac{\alpha_1 \gamma_{s_1}}{\alpha_2 \gamma_{s_2} + 1}$$

(5)

where $\gamma_{s_1} = \frac{p_s |h_{s_1}|^2}{\sigma^2}$. Assume that decoding $x_{1s}(t)$ succeeds, and $x_{1s}(t)$ can be perfectly subtracted from $\gamma_{12}$, so the SINR for decoding $x_{2s}(t)$ is written as

$$\gamma_{12}^{s_2} = \alpha_2 \gamma_{s_2}$$

(6)

For the direct link in the first time slot, U1 only decodes its own signal from BS with the signal including U2 thought as the interference. From (2), the SINR for decoding $x_{1s}(t)$ by U1 is given by

$$\gamma_{1s}^{s_1} = \frac{\alpha_1 \gamma_{s_1}}{\alpha_2 \gamma_{s_2} + 1}$$

(7)

where $\gamma_{s_1} = \frac{p_s |h_{s_1}|^2}{\sigma^2}$. On the other hand, provided that the forwarding signal from U2 in (4) is successfully decoded by U1, then the SINR of decoding $x_{1s}(t)$ can be represented as

$$\gamma_{2s}^{s_2} = \gamma_{12}$$

(8)

where $\gamma_{12} = \frac{p_s |h_{12}|^2}{\sigma^2}$.

With the use of MRC at U1, the total SINR of decoding $x_{1s}(t)$ can be represented as

$$\gamma_{DF} = \gamma_{1s}^{s_1} + \gamma_{2s}^{s_2} = \frac{\alpha_1 \gamma_{s_1}}{\alpha_2 \gamma_{s_2} + 1} + \gamma_{12}$$

(9)

2.2 AF Protocol

If U2 chooses AF mode to forward U1’s message, which is assumed to be successfully decoded by U2 in the second time slot, the signal received by U1 can be represented as

$$\gamma_{2s}^{AF}(t) = h_{1s}(t)F_1 x(t) + n_{1s}(t),$$

(10)

where

$$x(t) = \beta y_{1,2}(t),$$

(11)

and the amplification factor $\beta = \frac{p_s}{|h_{s1}|^2 + \sigma^2}$.

Since the received signal $y_{1,2}$ at U2 in the first time slot remains irrelevant to forwarding modes, for AF mode, the SINRs of sequentially decoding $x_{1s}$ and $x_{2s}(t)$ by U2 correspond to (5) and (6).

If U1 successfully decodes the signal from U2 in the second time slot, then the SINR of decoding its own $x_{1s}(t)$ can be expressed as

$$\gamma_{2s}^{AF} = \frac{\alpha_1 \gamma_{s_1}}{\alpha_2 \gamma_{s_2} + \gamma_{12} + \gamma_{2s} + 1}$$

(12)

Next, combined with (7) from the direct link and (12) from the AF forwarding link by leveraging on MRC, the SINR of decoding $x_{1s}(t)$ at U1 can be represented as

$$\gamma_{DF}^{AF} = \gamma_{1s}^{s_1} + \gamma_{2s}^{AF} = \frac{\alpha_1 \gamma_{s_1}}{\alpha_2 \gamma_{s_2} + 1} + \frac{\alpha_1 \gamma_{1s}}{\alpha_2 \gamma_{s_2} + \gamma_{12} + \gamma_{2s} + 1}$$

(13)

3 Outage Probability and System Throughput Analysis

3.1 Outage Probability of U2

For U2, the outage happens if it cannot decode U1’s message, or it can successfully decode U1’s message, but U2 is
unable to decode its own message. Hence, after a series of derivations, the outage probability of U2 is given by Theorem 1.

**Theorem 1**

$$P_{\text{out}} = 1 - \Pr \{ \gamma_{U1}^1 \geq \gamma, \gamma_{U2}^2 \geq \gamma \} = \begin{cases} 1 - e^{-\frac{\gamma}{x_2}} & \alpha_1 \leq \alpha_2 \gamma, \\ 1 - e^{-\frac{\gamma}{x_2}} & \alpha_1 > \alpha_2 \gamma \end{cases}$$

(14)

where $\gamma_1 = 2^{2R_1} - 1$, $\gamma_2 = 2^{2R_2} - 1$, and $R_i = \frac{1}{2} \log_2(1 + \gamma_i)$ represents the threshold rate, $i = 1, 2$.

The proof of Theorem 1 is given in Appendix A. Moreover, it should be pointed out that the outage probability of U2 is independent of the concrete forwarding protocols since it is computed in the first slot prior to the forwarding. In other words, different forwarding protocols only make an impact on the outage probability of U1. Therefore, in the following subsections, we will only provide an analysis on the outage probability of U1 with considered forwarding protocols.

### 3.2 Outage Probability with HDAF Protocol

In our system model, U2 can act as both a user and a relay, which requires to choose a proper forwarding protocol. In the previous papers [23–26], AF and DF are commonly used to forward messages. Nonetheless, AF amplifies not only the useful signal but also the noise. Although DF forwards a pure signal, the relay will remain silent if it fails to correctly decode this pure signal [7,8]. However, the disadvantages of the DF protocol can be overcome with the HDAF protocol adopted. In terms of HDAF [4,5,9], specifically, if the U1 signal is successfully decoded at the relay, the relay utilizes DF to forward U1, otherwise, it chooses AF to forward the U1 signal.

According to the above mentioned description about the HDAF protocol, the outage probability of U1 can be formulated as

$$P_{\text{out}}^{\text{HDAF}} = \Pr \left\{ \frac{\gamma_{U1}}{\gamma_{U1}^M_{\text{AF}}} < 1 \right\} + \Pr \left\{ \frac{\gamma_{U1}}{\gamma_{U1}^M_{\text{DF}}} < 1 \right\}$$

(15)

An approximate closed-form expression for (15) is given by Theorem 2, whose proof is given in Appendix B.

**Theorem 2**

1. When $\alpha_1 \leq \alpha_2 \gamma$, the analysis can be split into two cases:
   a. $P_{\text{out}}^{\text{HDAF}} = 1$, for $\gamma \geq \frac{2\alpha_1}{\alpha_2}$.
   b. For $\gamma < \frac{2\alpha_1}{\alpha_2}$, (15) is derived as

$$P_{\text{out}}^{\text{HDAF}} \approx 1 - \frac{\alpha_1}{\alpha_2} \gamma_2 \frac{\gamma}{\gamma_1} \prod_{k=1}^{K} \left( 1 - \theta_k e^{-\frac{\theta_k^2}{\gamma_2}} \left( \frac{\gamma_1}{\gamma_2} \right)^{\frac{1}{2} - \frac{1}{2\gamma_2}} \right) \times u_k K_1(u_k),$$

(16)

where $\theta_k = \left( \frac{\alpha_1 - \frac{\alpha_2}{2}}{\alpha_1 - \frac{\alpha_2}{2}} \right) x_k + \frac{\gamma}{2}, x_k = \cos\left( \frac{\theta_k - 1}{2} \pi \right), u_k = 2 \sqrt{\frac{\theta_k^2 + \theta_k - (1 - \alpha_2^2)(\alpha_1 - \alpha_2)^2}{2(1 - \alpha_2^2)(\alpha_1 - \alpha_2)^2}}$, and $K_1(\cdot)$ is the first-order modified Bessel function of the second kind [21].

2. When $\alpha_1 > \alpha_2 \gamma$, the solution of $P_{\text{out}}^{\text{HDAF}}$ is given by (17) at the top of next page, where $x_{k_1} = \cos\left( \frac{2\gamma_1 - 1}{2} \pi \right), x_{k_2} = \cos\left( \frac{2\gamma_2 - 1}{2} \pi \right), u_{k_1} = \sqrt{4(b_{3k}b_{2k} - b_{1k}b_{4k})/(\lambda_{12}b_{2k}^2)}, b_k = 1/(\alpha_1 - \alpha_2 \gamma_1) (x_{k_1} + 1), b_{1k} = \gamma_1 (1 + \alpha_2 b_k) - \alpha_1 b_k, b_{2k} = \gamma_1 (1 + b_k), b_{3k} = \lambda_{12}[(\alpha_1 - \alpha_2 \gamma_1)(1 + \alpha_2 b_k) + \alpha_1 \alpha_2 b_k], b_{4k} = \lambda_{12}[(\alpha_1 - \alpha_2 \gamma_1)(1 + b_k)].$

### 3.3 Outage Probability with IHDAF Protocol

Owing to limited battery, it is unfair for the strong user to always operate in the collaboration state. In this section, in order to further improve the outage performance of U1, more importantly, to make U2 cooperate when necessary, the IHDAF protocol [7,16,17] at U2 is adopted based on our cooperative NOMA model. For IHDAF scheme, U2 is invoked to forward U1’s message by relying on the aforementioned HDAF protocol only when the direct link transmission fails in the first time slot, otherwise, U2 remain silent in the second slot. Through the feedback information sent by U1, the base station can appraise whether U1 has successfully decoded its information, and further determine whether U2 participates in the collaboration. Meanwhile, the relay is also capable of knowing the decoding consequences of the direct link through the base station [16]. Here we assume that the base station can perfectly receive the feedback information [17]. Hence, the IHDAF protocol makes full utilization of the direct link to reduce the collaboration of U2, thus saving the energy consumption of the strong user.

#### 3.3.1 Outage Probability of U1 with IHDAF

Once U1 fails to decode its own signal from the direct link in the first slot, the decoding of U1 is only dependent on the forwarding link from U2. This implies that the received signal from the direct link is abandoned in the second slot. Under this situation with the IHDAF protocol, we can formulate the outage probability of U1 as

$$P_{\text{out}}^{\text{IHDAF}} = \Pr \{ \gamma_{U1}^{BS} < \gamma \} \{ \Pr \{ \gamma_{U1}^{AF} < \gamma, \gamma_{U1}^{AF} \geq \gamma \} \}$$

(18)

The closed-form solution of (18) is given by Theorem 3, whose proof is given in Appendix C.

**Theorem 3**

$$P_{\text{out}}^{\text{IHDAF}} = (1 - e^{-\frac{\gamma}{\alpha_1(\alpha_1 - \alpha_2 \gamma)}}) \left( 1 - e^{-\frac{\gamma}{\alpha_2(\alpha_1 - \alpha_2 \gamma)}} \right)$$

(19)
where (19) holds under the condition that \( \alpha_1 > \alpha_2 \gamma_1 \). Otherwise, \( p_{\text{out}}^{\text{HDAF}} = 1 \).

### 3.3.2 Outage Probability of U1 with IHDAF-MRC

If U1 fails to decode its own signal from the direct link in the first slot, its received signal from the direct link is retained and combined with the forwarding signal from U2 by using MRC in the second slot. We denote the scheme as IHDAF-MRC, in which the outage probability of U1 can be represented as (20) at the top of next page, where the expression of \( p_{\text{out}}^{\text{HDAF}} \) in (20) has been given by Theorem 2, and \( \Pr\{\gamma_{1,\text{BS}} < \gamma_1\} \) can be calculated as

\[
\Pr\{\gamma_{1,\text{BS}} < \gamma_1\} = \Pr\{(\alpha_1 - \alpha_2 \gamma_1) x_1 < \gamma_1\} = \begin{cases} 
1 & \alpha_1 \leq \alpha_2 \gamma_1 \\
1 - e^{-\frac{\gamma_1}{x_1}} & \alpha_1 > \alpha_2 \gamma_1 \end{cases}
\]

(21)

### 3.4 System Throughput

Given a threshold rate pair, the system throughput [18, 19] of the proposed model can be evaluated by taking the summation of individual rate scaled with the probability of successful reception at U2 and U1. Thus, we have

\[
S_T^{\text{IHDAF}} = (1 - P_{\text{out,1}}) R_2 + (1 - P_{\text{out,2}}) R_1
\]

(22)

Remark: As deduced from (22), for different forwarding protocols given a threshold rate pair \( (R_1, R_2) \), the system throughput is only influenced by the outage Probability \( P_{\text{out,1}} \) of U1 because \( P_{\text{out,2}} \) remains the same no matter what forwarding protocols are adopted. Moreover, \( P_{\text{out,1}} \) will be close to zero in high SNR region, and hence, the system throughput for different schemes will be identical. On the other hand, as the BS transmit power increases, both \( P_{\text{out,1}} \) and \( P_{\text{out,2}} \) tend to 0, and then the system throughput will converge to \( R_1 + R_2 \).

### 4 Numerical Results

For our considered user cooperation model, the system performance with IHDAF protocol is provided in this section. The validity of the derived analytic expressions is verified by Monte Carlo simulation. Unless otherwise stated, the default values of the system parameters are: \( P_2 = 20\text{dB} \), the power allocation factor \( \alpha_1 = 0.8 \), \( \alpha_2 = 0.2 \), and for convenience, the noise variance at each node is \( \sigma^2 = 1 \). The variances of channel gains are \( \lambda_x = 0.1 \), \( \lambda_y = 1 \), \( \lambda_z = 0.5 \). The threshold rate at U1 and U2 is \( R_1 = R_2 = 0.1 \). For the convenience of distinguishing the different schemes in this paper, we denote the schemes in Section 3.2, 3.3.1 and 3.3.2 as HDAF-MRC, IHDAF and IHDAF-MRC, respectively. Additionally, the suffixes ‘th’ and ‘appro’ in the legend refer to the theory and approximation, respectively. It is worth noting that the only one step difference between ‘th’ and ‘appro’ is that the latter makes an approximation to the integral in last step of outage derivation using Gauss-Chebyshev quadrature formula.

In Fig.2, we plot the outage probabilities of U1 and U2 under different forwarding protocols, all of which take advantage of MRC at U1 without adding specific notation in the legend. Obviously, the Monte Carlo simulation demonstrates the correctness of the derived outage probabilities for U1 and U2. We can observe that the outage performance of U1 in the HDAF mode has a slight improvement over the commonly used DF and AF modes. The reason is that U2 with HDAF can select DF or AF adaptively, namely U2 selects AF mode to forward the signal if DF mode fails to work. It can be seen that IHDAF is significantly superior to the other forwarding modes, which is due to the fact that U1 preferentially employs the direct link to decode and at the same time choose HDAF as a remediation.

From Fig.3, it is obvious that proposed IHDAF is much improved over the HDAF with SC scheme in [15]. This illustrates that the IHDAF-MRC greatly improves the outage performance of U1.

Fig.4 depicts the outage probability of U1 with different threshold rate \( R_1 \) as BS transmit power increases. We compare outage performance of three schemes: HDAF-MRC, IHDAF and IHDAF-MRC, whose closed-form expressions correspond to Theorem 2, Theorem 3 and (20). Strictly speaking, the equation (20) equals the product of Theorem 2 and (21). It can be noted that the outage probabilities of all three schemes significantly decrease as the target rate decreases. And IHDAF-MRC can achieve the best outage performance.
\[
\pi_{\text{IHDAF}}^{\text{out1}} = \Pr(\gamma_{x1}^u < \eta) \Pr(\gamma_{x1}^u \geq \gamma_{x1}^MRC < \bar{\eta}) + \Pr(\gamma_{x1}^u < \gamma_{x1}^\text{DF} < \bar{\eta}) \\
= \Pr(\gamma_{x1}^u < \gamma) \pi_{\text{HDAF}}^{\text{out1}}
\] (20)

\[\text{Outage Probability}
\]

\[\text{Outage Performance for different protocols}
\]

\[\text{Comparison of the outage performance with [15]}
\]
Moreover, in practice, IHDAF has the lower hardware implementation complexity than IHDAF-MRC. Accordingly, IHDAF would be also a better choice if it is acceptable to sacrifice a little performance to simplify the implementation of the weak user.

Given different threshold rate pairs for both users, the system throughput curves of three schemes are presented in Fig. 5. It can be observed that the throughput curves of all three schemes nearly overlap under any fixed threshold rate pair. The reason is that the system throughput increases as the threshold rate of the weak user is, the better its outage performance can be greatly improved with increase of BS transmit power, the system throughput gradually improves and reaches a fixed value. We can also notice that the system throughput increases as the threshold rate pair increases. These phenomena have been explained by the Remark in section 3.4.

5 Conclusion

In this paper, we derive approximate expressions of outage probabilities and system throughput for the proposed NOMA system with user collaborative IHDAF protocols. Simulation results and the analysis reveal that the outage performance of the weak user can be greatly improved with IHDAF protocol in a user cooperative system. The lower the threshold rate of the weak user is, the better its outage performance is. Moreover, the system throughput is confirmed to be insensitive to the different forwarding protocols especially at high SNRs. For the future work, we will attempt to extend the IHDAF protocol to other communication systems combined with current advanced technology such as full duplex and wireless energy harvesting.

6 Appendix

A The derivation of outage probability of U2

Proof of theorem 1 For U2, the probability without the outage occurrence is expressed as

\[
\Pr\{\gamma_{12}^{(2)} \geq \gamma ; \gamma_{21}^{(2)} \geq \gamma_{22}\} = \Pr\{\alpha_1 \geq \gamma_1, \alpha_2 \geq \gamma_2, \gamma \}
\]

where the right side holds with (5) and (6) plugged.

It is apparent that the computation of (23) can be split into the following two cases.
The derivation of outage probability of U1 with MRC

**Proof of theorem 2**  By substituting (5), (9) and (13) into (15), the outage probability of U1 with HDAF protocol is formulated as (26) at the top of next page. First, we derive the distribution function with respect to $\theta$ as

$$F_\theta(\theta) = 1 - e^{-\frac{\theta}{\theta_1}} \left( \frac{\theta}{\theta_2} \right)^{\frac{\alpha_1}{\alpha_2}} K_1(u),$$

where the variable $\theta = \frac{\alpha_1 \gamma_1 + \alpha_2 \gamma_2 + \gamma_1 \gamma_2}{\alpha_1 \gamma_1 + \alpha_2 \gamma_2 + \gamma_1 + \gamma_2 + 1}$, and the parameter $u = 4ab \sqrt{4ab}$, where $a = \frac{\alpha_1}{\alpha_1 + \alpha_2}$ and $b = \frac{1}{\lambda_1 (\alpha_1 - \alpha_2 \gamma_1)}$.

Furthermore, the pdf of $\theta$ can be given by

$$f_\theta(\theta) = \frac{dF_\theta(\theta)}{d\theta}, \hspace{0.5cm} 0 < \theta < \frac{\alpha_1}{\alpha_2}$$

The analytical calculation of the first term $\Pr\{\gamma_{1,2}^{U} \geq \gamma_1, \gamma_{DF}^{MRC} < \gamma_1\}$ in (26) can be split into two cases below:

- **a)** when $\alpha_1 - \alpha_2 \gamma_1 \leq 0$

$$\Pr\{\gamma_{1,2}^{U} \geq \gamma_1, \gamma_{DF}^{MRC} < \gamma_1\} = 0 $$

- **b)** when $\alpha_1 - \alpha_2 \gamma_1 > 0$, it can be obtained as from (23)

$$\Pr\{\gamma_{1,2}^{U} \geq \gamma_1, \gamma_{DF}^{MRC} < \gamma_1\} = e^{-\frac{\gamma_1}{\theta_1}} \int_{\gamma_2}^{\infty} \frac{1}{\gamma_2^{\frac{\alpha_1}{\alpha_2}} \lambda_2} d\gamma_2$$

After obtaining $\Pr\{\gamma_{1,2}^{U} \geq \gamma_1, \gamma_{DF}^{MRC} < \gamma_1\}$, we can get (14).

**B The derivation of outage probability of U1 with MRC**
\( P_{\text{out}}^{\text{DAF}} = \Pr(\gamma_{1/2}^{u} \geq \gamma_{\text{MRC}}^{\text{AF}} < \gamma_{1}) + \Pr(\gamma_{1/2}^{u} < \gamma_{\text{MRC}}^{\text{AF}} < \gamma_{1}) \)

\[
= \Pr((\alpha_{1} - \alpha_{2} \gamma_{1}) \gamma_{1/2} \geq \gamma_{1}, (\alpha_{1} - \alpha_{2} (\gamma_{1} - \gamma_{2})) \gamma_{1/2} < \gamma_{1} - \gamma_{2}) + \Pr((\alpha_{1} - \alpha_{2} \gamma_{1}) \gamma_{1/2} < \gamma_{1}, [(\alpha_{1} - \alpha_{2} (\gamma_{1} - \theta)) \gamma_{1/2} < \gamma_{1} - \gamma_{1} - \theta])
\]

(26)

and

\[
Q_{2} = \Pr(\gamma_{1/2} < \gamma_{2}) = \frac{1}{\lambda_{12}} \int_{0}^{\gamma_{2}} e^{-\frac{\gamma_{2}}{\lambda_{12}}} \frac{x_{2}}{2} dx
\]

\[
= 1 - e^{-\frac{\gamma_{2}}{\lambda_{12}}} - \frac{\gamma_{2}}{2} \int_{0}^{\gamma_{2}} \frac{e^{-\frac{\gamma_{2}}{\lambda_{12}}} \gamma_{2}^{(1-x)}}{\lambda_{12}} dx
\]

(33)

It is difficult to obtain an exact integral result for \( Y \) in (33). However, we can use the Gauss-Chebyshev quadrature formula to get its approximate solution, which is expressed as

\[
Q_{2} \approx 1 - e^{-\frac{\gamma_{2}}{\lambda_{12}}} - \frac{\gamma_{2} \pi}{2 \lambda_{12}} e^{\frac{-\gamma_{2} \pi}{2 \lambda_{12}}} \times \prod_{k=1}^{K} \sqrt{1 - \xi_{k}^{2}} e^{-\frac{\gamma_{2} \pi}{2 \lambda_{12}}} \frac{\gamma_{2} \pi}{2 \lambda_{12}} ,
\]

(34)

where \( \lambda_{k} = \cos(\frac{(2k-1) \pi}{2K}) \).

Similarly, the computation of the second term \( \Pr(\gamma_{1/2}^{u} < \gamma_{1}, \gamma_{\text{MRC}}^{\text{AF}} < \gamma_{1}) \) in (26) is also divided into the following two circumstances.

a) When \( \alpha_{1} - \alpha_{2} \gamma_{1} \leq 0 \)

a.1) When \( \gamma_{1} - \alpha_{2} \gamma_{1} < \alpha_{1} \gamma_{1} \)

\[
\Pr(\gamma_{1/2}^{u} < \gamma_{1}, \gamma_{\text{MRC}}^{\text{AF}} < \gamma_{1}) = \Pr(\gamma_{2} > \frac{\gamma_{1}}{\alpha_{1} - \alpha_{2} \gamma_{1}}, \gamma_{1} > \frac{\gamma_{1} - \theta}{\alpha_{1} - \alpha_{2} (\gamma_{1} - \gamma_{2})})
\]

\[
= \Pr(\gamma_{2} > \frac{\gamma_{1}}{\alpha_{1} - \alpha_{2} \gamma_{1}}, \gamma_{1} > \frac{\gamma_{1} - \theta}{\alpha_{1} - \alpha_{2} (\gamma_{1} - \gamma_{2})})
\]

\[
= \Pr(\gamma_{1/2} > \frac{\gamma_{1} - \theta}{\alpha_{1} - \alpha_{2} (\gamma_{1} - \gamma_{2})})
\]

\[
= \int_{0}^{\gamma_{1} - \theta} f_{\Theta}(\theta) d\theta.
\]

(35)

a.2) When \( \gamma_{1} - \alpha_{2} (\gamma_{1} - \gamma_{2}) > 0 \)

\[
\Pr(\gamma_{1/2}^{u} < \gamma_{1}, \gamma_{\text{MRC}}^{\text{AF}} < \gamma_{1}) = \int_{0}^{\gamma_{1} - \theta} f_{\Theta}(\theta) d\theta + \int_{\gamma_{1} - \theta}^{\gamma_{1}} \frac{\gamma_{2}^{\theta}}{\lambda_{12}^{\theta}} e^{-\gamma_{1}} (1 - \frac{\gamma_{2}^{\theta}}{\lambda_{12}^{\theta}}) \Gamma_{1}(u_{k} K_{1}(u_{k}), \theta) d\theta.
\]

b) When \( \alpha_{1} - \alpha_{2} \gamma_{1} > 0 \)

In this case, the outage probability can be computed as (40) at the top of next page. However, it is intractable to obtain its exact result by conventional methods. We can simplify it by using the Gauss-Chebyshev quadrature formula to obtain its approximation, which is represented as

\[
\Xi \approx \frac{\gamma_{2} \pi}{2 \lambda_{12} K_{1}(\alpha_{1} - \alpha_{2} \gamma_{1})} \sum_{k=1}^{K_{1}} \sqrt{1 - \xi_{k}^{2}} \frac{b_{3k}}{b_{3k}} e^{\frac{-b_{3k}^{2}}{2 \lambda_{12}^{2} b_{3k}}} e^{\frac{-b_{3k}^{2}}{2 \lambda_{12}^{2} b_{3k}}} dt.
\]

(41)
\( \Pr(\gamma_{1,2}^{U} < \gamma, \gamma_{MF}^{U} < \gamma) = \Pr(\gamma_{2} < \frac{\gamma}{\alpha_{1} - \alpha_{2} \gamma}, \gamma_{1} < \frac{\gamma - \theta}{\alpha_{1} - \alpha_{2} (\gamma - \theta)}) \)
\[
= \int_{0}^{\gamma_{2}} \int_{0}^{\gamma_{1}} \frac{1}{\lambda_{12} \lambda_{23}} \left(1 - e^{-\frac{\gamma_{1}}{\alpha_{1} - \alpha_{2} \gamma}} - e^{-\frac{\gamma_{2}}{\alpha_{1} - \alpha_{2} (\gamma - \theta)}} - e^{-\frac{\gamma_{1} + \gamma_{2}}{\alpha_{1} - \alpha_{2} (\gamma - \theta)}} + e^{-\frac{\gamma_{1}}{\alpha_{1} - \alpha_{2} \gamma}} + e^{-\frac{\gamma_{2}}{\alpha_{1} - \alpha_{2} (\gamma - \theta)}} + e^{-\frac{\gamma_{1} + \gamma_{2}}{\alpha_{1} - \alpha_{2} (\gamma - \theta)}} \right) d\gamma_{2} d\gamma_{1}. \tag{40} \]

where \( x_{12} = \cos\left(\frac{2\pi x_{m}}{2\lambda_{1}}\right), b_{k} = \frac{\gamma_{1}}{\alpha_{1} - \alpha_{2} \gamma}(x_{k} + 1), b_{1k} = \gamma_{1}(1 + \alpha_{2} b_{k}) - \alpha_{1} b_{k}, b_{2k} = \gamma_{1}(1 + b_{k}), b_{3k} = \lambda_{12}[(\alpha_{1} - \alpha_{2} \gamma)(1 + \alpha_{2} b_{k}) + \alpha_{1} \alpha_{2} b_{k}], b_{3k} = \lambda_{12}(\alpha_{1} - \alpha_{2} \gamma)(1 + b_{k}). \)

In follows, we calculate \( \Delta \) as
\[
\Delta = \int_{0}^{\infty} e^{-\frac{b_{3k} - b_{4k} \gamma_{1}}{\lambda_{12} \lambda_{23}} - \frac{1}{\lambda_{12} \lambda_{23}} \frac{1}{\lambda_{12} \lambda_{23}} d\gamma_{1}} \]
\[
\int_{0}^{\infty} e^{-\frac{b_{3k} - b_{4k} \gamma_{1}}{\lambda_{12} \lambda_{23}} - \frac{1}{\lambda_{12} \lambda_{23}} \frac{1}{\lambda_{12} \lambda_{23}} d\gamma_{1}} \]
\[
= \lambda_{12} b_{3k} u_{k} K_{1}(u_{k}) - \left[ \int_{0}^{\infty} e^{-\frac{b_{3k} - b_{4k} \gamma_{1}}{\lambda_{12} \lambda_{23}} - \frac{1}{\lambda_{12} \lambda_{23}} \frac{1}{\lambda_{12} \lambda_{23}} d\gamma_{1}} \right] \tag{42} \]

where \( u_{k} = \sqrt{\frac{4b_{3k} - b_{4k} \gamma_{1}}{\lambda_{12} \lambda_{23}}}. \) Likewise, since it is difficult to directly solve the integral in (42), by applying Gauss-Chebyshev quadrature formula, \( \Phi \) can be approximated as
\[
\Phi \approx \frac{b_{3k} \pi}{2K_{2}} \sum_{k=1}^{K_{2}} \sqrt{1 - x_{3k}^{2}} e^{-\frac{b_{3k} - b_{4k} \gamma_{1}}{\lambda_{12} \lambda_{23}} - \frac{1}{\lambda_{12} \lambda_{23}} \frac{1}{\lambda_{12} \lambda_{23}} \frac{1}{\lambda_{12} \lambda_{23}}}, \tag{43} \]

where \( x_{3k} = \cos(\frac{2\pi x_{m}}{2\lambda_{1}}). \) Finally, we substitute (41), (42), and (43) into (40) and acquire the result in (17).

C The derivation of outage probability of U1 with IHDAF

Proof of theorem 3 Combined with (5), (7), (9) and (13), the outage probability of the weak user is formulated as (44) at the top of next page.

a) When \( \alpha_{1} - \alpha_{2} \gamma_{1} > 0 \)
\[
\Pr\{\gamma_{1,2}^{UB} < \gamma, \gamma_{MF}^{UB} < \gamma\} = \Pr(\gamma_{2} < \frac{\gamma}{\alpha_{1} - \alpha_{2} \gamma}, \gamma_{1} < \frac{\gamma - \theta}{\alpha_{1} - \alpha_{2} (\gamma - \theta)}), \gamma_{2} < \gamma \}
\]
\[
\Delta = \Pr(\gamma_{1} < \frac{\gamma}{\alpha_{1} - \alpha_{2} \gamma}) \Pr(\gamma_{2} < \gamma) \Pr(\gamma_{2} < \gamma) \]
\[
= (1 - e^{-\frac{\gamma_{1}}{\alpha_{1} - \alpha_{2} \gamma}})(1 - e^{-\frac{\gamma_{2}}{\alpha_{2} (\gamma - \theta)}}) \tag{45} \]

where \( \Delta \) holds due to the mutual independence between \( \gamma_{1}, \gamma_{2}, \gamma_{2} \) and \( \gamma_{2} \).

\[
\Pr\{\gamma_{1,2}^{UB} < \gamma, \gamma_{MF}^{UB} < \gamma\} \]
\[
= \Pr(\gamma_{2} < \frac{\gamma}{\alpha_{1} - \alpha_{2} \gamma}) \Pr(\gamma_{2} < \frac{\gamma}{\alpha_{1} - \alpha_{2} \gamma}), \gamma_{2} \}
\]
\[
\approx \Pr(\gamma_{2} < \frac{\gamma}{\alpha_{1} - \alpha_{2} \gamma}) \Pr(\gamma_{2} < \frac{\gamma}{\alpha_{1} - \alpha_{2} \gamma}), \gamma_{2} \}
\]
\[
= \Pr(\gamma_{2} < \frac{\gamma}{\alpha_{1} - \alpha_{2} \gamma}), \gamma_{2} < \frac{\gamma}{\alpha_{1} - \alpha_{2} \gamma}, \gamma_{2} < \gamma \}
\]
\[
= \Pr(\gamma_{2} < \frac{\gamma}{\alpha_{1} - \alpha_{2} \gamma}), \gamma_{2} < \frac{\gamma}{\alpha_{1} - \alpha_{2} \gamma}, \gamma_{2} < \gamma \}
\]
\[
= \Pr(\gamma_{2} < \frac{\gamma}{\alpha_{1} - \alpha_{2} \gamma}), \gamma_{2} < \frac{\gamma}{\alpha_{1} - \alpha_{2} \gamma}, \gamma_{2} < \gamma \}
\]
\[
= \Pr(\gamma_{2} < \frac{\gamma}{\alpha_{1} - \alpha_{2} \gamma}), \gamma_{2} < \frac{\gamma}{\alpha_{1} - \alpha_{2} \gamma}, \gamma_{2} < \gamma \}
\]
\[
= \Pr(\gamma_{2} < \frac{\gamma}{\alpha_{1} - \alpha_{2} \gamma}), \gamma_{2} < \frac{\gamma}{\alpha_{1} - \alpha_{2} \gamma}, \gamma_{2} < \gamma \}
\]
\[
= \Pr(\gamma_{2} < \frac{\gamma}{\alpha_{1} - \alpha_{2} \gamma}), \gamma_{2} < \frac{\gamma}{\alpha_{1} - \alpha_{2} \gamma}, \gamma_{2} < \gamma \}
\]
\[
= \Pr(\gamma_{2} < \frac{\gamma}{\alpha_{1} - \alpha_{2} \gamma}), \gamma_{2} < \frac{\gamma}{\alpha_{1} - \alpha_{2} \gamma}, \gamma_{2} < \gamma \}
\]
\[
= \Pr(\gamma_{2} < \frac{\gamma}{\alpha_{1} - \alpha_{2} \gamma}), \gamma_{2} < \frac{\gamma}{\alpha_{1} - \alpha_{2} \gamma}, \gamma_{2} < \gamma \}
\]

Then based on (47) and (48), it follows that

\[
\Pr\{\gamma_{2} < \frac{\gamma}{\alpha_{1} - \alpha_{2} \gamma}, \gamma_{2} < \gamma \}
\]
\[
= \Pr(\gamma_{2} < \frac{\gamma}{\alpha_{1} - \alpha_{2} \gamma}, \gamma_{2} < \gamma \}
\]
\[
= \Pr(\gamma_{2} < \frac{\gamma}{\alpha_{1} - \alpha_{2} \gamma}, \gamma_{2} < \gamma \}
\]

Therefore, the equation (19) can be obtained from (18), (45) and (49).

b) When \( \alpha_{1} - \alpha_{2} \gamma_{1} < 0 \), it is easy to obtain \( P_{out1}^{IHDAF} = 1 \).

The proof of Theorem 3 is completed.

Acknowledgements This work was supported in part by National Natural Science Foundation of China (No. 61501315; No. 62072325), Scientific and Technological Innovation Programs of Higher Education Institutions (2015169) and Innovation Team (201705D131025) of Shaxi Province.
\[ P_{\text{IHDAF out}} = \Pr \{ y_{1,BS}^2 < \gamma \} \left[ \Pr \{ y_{1,BS}^2 < \gamma, y_{1,2}^2 \geq \gamma, z_{DF}^2 < \gamma \} + \Pr \{ y_{1,BS}^2 < \gamma, y_{1,2}^2 < \gamma, z_{DF}^2 \geq \gamma \} \right] \\
= \Pr \{ (\alpha_1 - \alpha_2) y_{1,1} < \gamma \} \left[ \Pr \{ (\alpha_1 - \alpha_2) y_{1,2} \geq \gamma, y_{1,2} < \gamma \} + \Pr \{ (\alpha_1 - \alpha_2) y_{1,2} < \gamma, (\alpha_1 - \alpha_2) y_{1,2} - y_{1,2} y_{1,2} < \gamma \} \right] \] (44)

Declarations:
We would like to declare that the work described is original research that has not been published previously, and not under consideration for publication elsewhere, in whole or in part. All the authors listed have approved the manuscript. No conflict of interest exists in the submission of this manuscript, which is approved by all authors for publication.

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