Performance Analysis of Multiuser Multiple Antenna Relaying Networks with Co-Channel Interference and Feedback Delay

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***Abstract*—This paper presents a comprehensive performance analysis of multiuser multiple antenna amplify-and-forward relaying networks employing opportunistic scheduling with feedback delay and co-channel interference over Rayleigh fading channels. Specifically, we derive exact as well as approximate closed-form expressions for the outage probability and average symbol error rate (SER) of the system. In addition, simple asymptotic expressions at the high signal-to-noise ratio (SNR) regime are obtained, which facilitate the characterization of the achievable diversity order and coding gain of the system. Moreover, two novel ergodic capacity bounds valid for general systems with arbitrary number of antennas and users are proposed. Finally, the optimum power allocation scheme in terms of minimizing the average SER is studied, and simple analytical solutions are obtained. Simulation results are provided to corroborate the derived analytical expressions, and it is demonstrated that the ergodic capacity bounds remain sufficiently tight across the entire range of SNRs and the proposed power allocation scheme offers significant improvements on the SER performance. The findings of the paper suggest that the full diversity order can only be achieved when there is ideal feedback, i.e., no feedback delay, and the diversity order always reduces to one in the presence of feedback delay. Also, the impact of key parameters such as the number of antennas and users on the system performance is intimately dependent on the level of feedback delay.**

***Index Terms*—Amplify-and-forward (AF) relaying, multiple antenna system, feedback delay, co-channel interference (CCI), multiuser diversity, power allocation.**

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I. Introduction

THE relaying technique has been demonstrated as a promising solution to extend the coverage and to improve the throughput of wireless communication systems [1], and hence has received considerable interests from both academia and industry. Recently, a novel network architecture, referred to as multiuser relaying networks, has been proposed and adopted in a number of industry standards such as IEEE 802.16j mobile multi-hop relaying [2] and IEEE 802.11s mesh networks [3]. Meanwhile, a significant amount of effort has been devoted to investigate the key performance measures such as outage probability, average symbol error rate (SER) and ergodic capacity of multiuser relaying networks with single antenna terminals over various fading channels (see [4]–[10] and references therein).

In an effort to further improve the performance of the multiuser relaying networks, a number of works has suggested the idea of incorporating the multiple antenna technique into the system [11]–[14]. Assuming multiple antennas at the source and destination, the work [11] investigated the transmit antenna selection and maximal ratio combining (TAS/MRC) scheme in multiuser relaying networks employing opportunistic scheduling, in which the destination with the highest instantaneous signal-to-noise ratio (SNR) is scheduled for transmission. Considering a multiple antenna source, the work [12] investigated the performance of orthogonal space-time block coding transmission in a downlink multiuser amplify-and-forward (AF) relaying system with the normalized SNR-based scheduling. In [13], the authors evaluated the average throughput of a multiuser multiple-input multiple-output (MIMO) relaying system with the channel state information (CSI)-assisted AF protocol. In [14], the authors derived the exact and asymptotic SER of multiuser MIMO relaying networks in non-identical Nakagami-m fading channels.

While these prior works have significantly improved our understanding on the impact of multiple antennas on the performance of multiuser relaying networks, the key limitation of these aforementioned works is that they all assume the noise-limited scenario. However, due to aggressive frequency reuse, future wireless communication networks will inevitably be subjected to co-channel interference (CCI). Based on this important observation, several works have investigated the impact of CCI on the performance of multiple antenna relaying networks in a variety of different scenarios. In [15], the authors derived the new analytical upper and lower capacity bounds of dual-hop multiple antenna AF relaying systems assuming the interference-limited relay. In [16], the effect of feedback delay on the performance of dual-hop beamforming AF networks with interference-limited relay was investigated in Rayleigh fading channels. In [17], the authors derived the exact and asymptotic outage probability of MIMO relaying networks using maximum ratio transmission and maximum ratio combining (MRT/MRC) in an interference-limited environment. In [18], the outage performance of dual-hop multiple antenna AF relaying systems employing fixed-gain or variable-gain relaying schemes with a single Rayleigh interferer at the relay was investigated. However, all these works are limited to the single user scenarios. Only in the recent work [19], the author investigated the outage probability of a multiuser single antenna AF relaying system employing opportunistic scheduling.

It is worth pointing out that most of the prior works assume perfect channel information state (CSI) of all the links. Due to the time varying nature of fading channels, the availability of perfect CSI is difficult in practise. Hence, the authors in [20] analyzed the impact of the outdated channel estimates on the performance of cooperative communications with optimal relay selection. In [21], the authors designed a relay selection strategy in AF cooperative networks with outdated CSI to minimize the average symbol error probability. In [22], the authors studied the effect of outdated CSI on the outage and error rate performance of AF system with best relay selection and partial relay selection, respectively. In [23], the authors analyzed the outage performance of partial relay selection with feedback delay. In [24] the authors investigated the decremental effect of beamforming with feedback delay on the performance of a two-hop AF relay network over Rayleigh-fading channels. In [25], the authors analyzed the impact of channel estimation errors and feedback delay on the achievable information rate of MIMO AF relay networks with relay precoder design. However, all these works only considered the single user scenario, and most of them neglected the impact of CCI on the system performance.

Motivated by these observations, in this paper, we consider a multiuser multiple antenna CSI-assisted AF relaying networks employing MRT/MRC with CCI and feedback delay over Rayleigh fading channels. To exploit the multiuser diversity, a single destination with the highest instantaneous SNR of the second hop is scheduled for transmission. In addition, we adopt a rather realistic assumption on the available CSI at the transmitter, i.e., the transmitter can only acquire the delayed CSI. For such practical system model, we pursue a comprehensive analysis of the joint effect of feedback delay and CCI on the performance of multiuser multiple antenna relaying networks. In a related work [26], the authors proposed a new threshold-based selection scheme for multi-relay and multiuser systems based on one-bit feedback. However, the analysis is limited to the single antenna system and the noised-limited environment. To the best of the authors' knowledge, the performance of multiuser multiple antenna relaying networks with CCI and feedback delay has not been reported. The main contributions of the paper are summarized as follows:

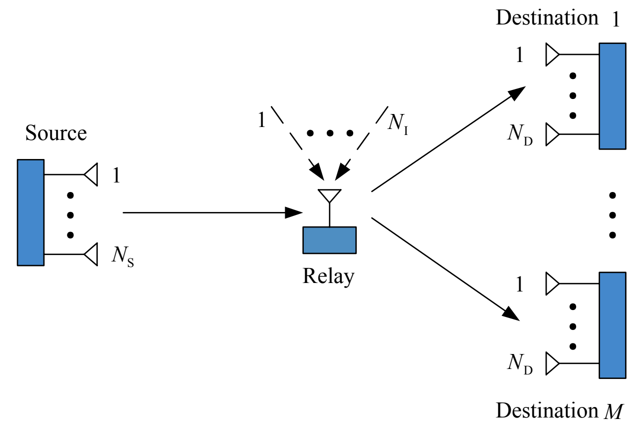

Fig. 1. System model.

- We first present a single integral expression for the exact outage probability of the system, and then derive tight closed-form lower bounds for the outage probability and average SER of the system, which provide an efficient means to evaluate the impact of key system parameters on the system performance.
- To gain further insights, we look into the high signal-to-noise ratio (SNR) regime, and provide simple and informative high SNR approximations for the outage probability and the average SER, which facilitate the complete characterization of the achievable diversity order and coding gain of the system.
- We propose novel upper and lower bounds for the ergodic capacity of the system, which are very general and are applicable to the systems with arbitrary number of interferers, antennas and users at any SNRs. Moreover, they are generally quite tight and become asymptotically exact in the high SNR regime.
- The optimum power allocation scheme in terms of minimizing the asymptotic average SER of the system is studied under the constraint that the total transmit power is fixed in the system, and closed-form expressions are derived. Simulation results demonstrate that a significant reduction in the SER is achieved using the optimal power allocation compared to the uniform power allocation.

The remainder of the paper is organized as follows. Section II introduces the system model. In Section III, we present a set of new analytical expressions for the key performance measures such as outage probability, average SER and ergodic capacity. In Section IV, the optimum power allocation scheme in terms of minimizing the asymptotic average SER is studied. Numerical results and discussions are provided in Section V. Finally, Section VI concludes the paper and summarizes the findings.

Notations: We use bold lower case letters to denote vectors and lower case letters to denote scalers, respectively. The probability function (PDF) and the cumulative distribution function (CDF) of a random variable (RV) X are denoted as $f_X(\cdot)$ and $F_X(\cdot)$, respectively. The symbol $\|\cdot\|_F$ denotes the Frobenius norm, $\mathrm{E}[\cdot]$ stands for the expectation operator, $(\cdot)^T$ denotes the transpose operator and $(\cdot)^\dagger$ denotes the conjugate transpose operator.

II. System Model

Let us consider a multiuser multiple antenna AF relaying network as illustrated in Fig. 1, where the source communicates with M destinations with the help of a single antenna relay. It is assumed that the source and each destination are equipped with $N_{\rm S}$ and $N_{\rm D}$ antennas, respectively. Moreover, we assume that the relay node is subjected to $N_{\rm I}$ interferers and additive white Gaussian noise (AWGN) while each destination node is corrupted by AWGN only. This scenario is also particularly relevant to frequency division relaying systems [27]–[31] where the relay and destination terminals experience different interference patterns. We also assume that all links are subject to Rayleigh fading, which is applicable in a no line of sight and rich scattering propagation environment.

The entire communication between the source and the destination consists of two orthogonal phases. During the first phase, the source transmits signal symbol to the relay node, and the signal received at the relay node can be expressed as

$$y_r = \sqrt{P_s}\mathbf{h}_1^\dagger \mathbf{w}_1 x_1 + \sum_{i=1}^{N_{\rm I}} \sqrt{P_{ir}} h_{ir} x_{ir} + n_r, \tag{1}$$

where P_s is the transmit power at the source, $\mathbf{h}_1$ is the $N_{\rm S} \times 1$ channel vector for the source-relay link, and its entries follow independent and identically distributed (i.i.d.) complex Gaussian distribution with zero-mean and variance λ_1, $\mathbf{w}_1$ is the transmit beamforming vector, x_1 is the source symbol with ${\rm E}\left[|x_1|^2\right] = 1$, $\{P_{ir}\}_{i=1}^{N_{\rm I}}$ are the transmit powers of the $N_{\rm I}$ interference signals, $\{h_{ir}\}_{i=1}^{N_{\rm I}}$ are the channel coefficients of the $N_{\rm I}$ interfering links with ${\rm E}\left[|h_{ir}|^2\right] = \lambda_{ir}$, $\{x_{ir}\}_{i=1}^{N_{\rm I}}$ are the $N_{\rm I}$ interference signals with ${\rm E}\left[|x_{ir}|^2\right] = 1$, and n_r is the AWGN noise at the relay node with ${\rm E}\left[|n_r|^2\right] = \sigma^2$.

To maximize the instantaneous SNR at the relay, the transmitter simply applies the Maximum Ratio Transmission (MRT) principle and steers the signal along the direction matching the first hop channel. However, such operation requires the perfect CSI of the first hop, which is unfortunately a very challenging task. In practice, it is more realistic that the transmitter utilizing a feedback link could acquire a delayed version of the CSI of the first hop $\widetilde{\mathbf{h}}_1$, which is then employed to design the transmit beamforming vector, i.e., $\mathbf{w}_1 = \frac{\widetilde{\mathbf{h}}_1}{\left\|\widetilde{\mathbf{h}}_1\right\|_F}$. The relation between $\widetilde{\mathbf{h}}_1$ and $\mathbf{h}_1$ can be modeled as [32]–[34]

$$\mathbf{h}_1 = \rho_1 \widetilde{\mathbf{h}}_1 + \sqrt{1-\rho_1^2}\mathbf{e}_1, \tag{2}$$

where $\mathbf{e}_1$ is an $N_{\rm S} \times 1$ error vector, and its elements are complex Gaussian random variables with zero-mean and variance λ_1. ρ_1 is the time correlation coefficient, which is defined to qualify the feedback information. According to Jakes' autocorrelation model [35], we have $\rho_1 = J_0(2\pi f_1 \tau_1)$, where f_1 is the maximum Doppler frequency, $J_0(\cdot)$ is the zeroth-order Bessel function of the first kind [36, Eq. (8.411)] and τ_1 is the time delay due to the feedback of CSI.

At the second phase, the relay node transmits a transformed version of the received signal to the destination after applying a gain factor G. For variable gain relaying scheme, the relaying gain G is given by [1], [27]–[29]

$$G = \sqrt{\frac{P_r}{P_s\left|\mathbf{h}_1^\dagger \mathbf{w}_1\right|^2 + \sum\limits_{i=1}^{N_{\rm I}} P_{ir}|h_{ir}|^2 + \sigma^2}}, \tag{3}$$

where P_r is the transmit power of the relay node. Hence, the received signal at the mth destination, after MRC processing, is expressed as

$$y_m = G\mathbf{w}_2^\dagger \mathbf{h}_{2m}\left(\sqrt{P_s}\mathbf{h}_1^\dagger \mathbf{w}_1 x_0 + \sum_{i=1}^{N_{\rm I}} \sqrt{P_i} h_{ir} x_i + n_r\right) + \mathbf{w}_2^\dagger \mathbf{n}_m, \tag{4}$$

where $\mathbf{h}_{2m}$ is the $N_{\rm D} \times 1$ channel link vector between the relay node and the mth destination, and its entries follow i.i.d. complex Gaussian distribution with zero-mean and variance λ_2, $\mathbf{w}_2$ is the $N_{\rm D} \times 1$ weight vector defined as $\mathbf{w}_2 = \frac{\mathbf{h}_{2m}}{\|\mathbf{h}_{2m}\|_F}$, $\mathbf{n}_m$ is the AWGN at the mth destination with ${\rm E}\left[\mathbf{n}_m \mathbf{n}_m^\dagger\right] = \sigma^2\mathbf{I}$.

Substituting (3) into (4), the instantaneous end-to-end SINR for the mth destination can be derived as

$$\gamma_m = \frac{\widetilde{\gamma}_1 \gamma_{2m}}{\widetilde{\gamma}_1 + (\gamma_{2m}+1)(\gamma_3+1)}, \tag{5}$$

where $\widetilde{\gamma}_1 = \frac{P_s}{\sigma^2}\left|\mathbf{h}_1^\dagger \mathbf{w}_1\right|^2$, $\gamma_{2m} = \frac{P_r}{\sigma^2}\|\mathbf{h}_{2m}\|_F^2$, and $\gamma_3 = \sum\limits_{i=1}^{N_{\rm I}} \frac{P_{ir}}{\sigma^2}|h_{ir}|^2$.

To exploit the multiuser diversity inherent in multiuser communications systems, we adopt the opportunistic scheduling scheme proposed in [37]. In such systems, the relay first identifies and selects the user with the best relay-destination link, and then feeds back the index of the desired destination to the source. Under this scheme, the instantaneous SNR of the second-hop link is given by

$$\gamma_2 = \max_{1\le m\le M}(\gamma_{2m}). \tag{6}$$

Once again, when the opportunistic scheduling is implemented, we consider the practical scenario that a delay exists between the user selection phase and the data transmission phase. Hence, the actual end-to-end SINR associated with the scheduled destination is expressed as

$$\gamma_{\rm D} = \frac{\widetilde{\gamma}_1 \widetilde{\gamma}_2}{\widetilde{\gamma}_1 + (\widetilde{\gamma}_2+1)(\gamma_3+1)}, \tag{7}$$

where $\widetilde{\gamma}_2$ is the τ_2 time-delayed version of γ_2. Let $\widetilde{\gamma}_{2m}$ be the τ_2 time-delayed version of γ_{2m}, and is given by $\widetilde{\gamma}_{2m} = \frac{P_r}{\sigma^2}\left\|\widetilde{\mathbf{h}}_{2m}\right\|_F^2$, where $\widetilde{\mathbf{h}}_{2m}$ is a delayed version of the instantaneous CSI for the link between the relay node and the mth destination. According to [32]–[34], we can model the relation between $\widetilde{\mathbf{h}}_{2m}$ and $\mathbf{h}_{2m}$ as

$$\mathbf{h}_{2m} = \rho_2 \widetilde{\mathbf{h}}_{2m} + \sqrt{1-\rho_2^2}\mathbf{e}_2, \tag{8}$$

where $\mathbf{e}_2$ is an $N_{\rm D} \times 1$ error vector, and its elements are complex Gaussian random variables with zero-mean and variance λ_2, ρ_2 is the correlation coefficient between $\widetilde{\mathbf{h}}_{2m}$ and $\mathbf{h}_{2m}$. For Jakes' autocorrelation model [35], $\rho_2 = J_0(2\pi f_2 \tau_2)$, where f_2 is the maximum Doppler frequency.

III. End-to-End Performance Analysis

In this section, we present a comprehensive performance investigation on the system described in the previous section. Specifically, we derive closed-form expressions for the three important performance metrics, i.e., the outage probability, the average SER, and the ergodic capacity. Before delving into the details, we first present a set of statistical properties of $\widetilde{\gamma}_1$, $\widetilde{\gamma}_2$ and γ_3, which will be frequently invoked in the subsequent derivations. Please note, the statistical properties of $\widetilde{\gamma}_1$ and γ_3 have been derived in [33] and [17], respectively. They are presented here to make this paper self-contained and also to improve the readability of the paper.

Lemma 1. *The exact PDF and CDF of $\widetilde{\gamma}_1$ are given by*

$$f_{\widetilde{\gamma}_1}(x) = \sum_{n=0}^{N_{\rm S}-1} \frac{\beta_n}{(N_{\rm S}-n-1)!\overline{\gamma}_1}\left(\frac{x}{\overline{\gamma}_1}\right)^{N_{\rm S}-n-1} e^{-\frac{x}{\overline{\gamma}_1}} \tag{9}$$

and

$$F_{\widetilde{\gamma}_1}(x) = 1 - \sum_{n=0}^{N_{\rm S}-1}\sum_{k=0}^{N_{\rm S}-n-1} \frac{\beta_n}{k!}\left(\frac{x}{\overline{\gamma}_1}\right)^{k} e^{-\frac{x}{\overline{\gamma}_1}}, \tag{10}$$

where $\overline{\gamma}_1 = \frac{P_s\lambda_1}{\sigma^2}$ is the average SNR of the first-hop link and $\beta_n = C_n^{N_{\rm S}-1}\rho_1^{2(N_{\rm S}-n-1)}\left(1-\rho_1^2\right)^n$ with $C_n^{N_{\rm S}-1} = \frac{(N_{\rm S}-1)!}{n!(N_{\rm S}-n-1)!}$ being the binomial coefficient.

Proof: The proof can be found in [33]. ■

Lemma 2. *The exact PDF of $\widetilde{\gamma}_2$ is given by* (11)*, where $\overline{\gamma}_2 = \frac{P_r\lambda_2}{\sigma^2}$ is the average SNR at the second-hop link, $\zeta = 1 + m(1-\rho_2)$, $\varphi = \sum_{q=1}^{N_{\rm D}-1} m_q$, and*

$$\Phi = \sum_{m_1=0}^{m}\sum_{m_2=0}^{m_1}\cdots\sum_{m_{N_{\rm D}-1}=0}^{m_{N_{\rm D}-2}} \frac{m!}{m_{N_{\rm D}-1}!}\prod_{t=1}^{N_{\rm D}-1}\frac{(t!)^{m_{t+1}-m_t}}{(m_{t-1}-m_t)!} \tag{12}$$

with $m_0 = m$ and $m_{N_{\rm D}} = 0$.

Proof: See Appendix A. ■

Lemma 3. *The PDF of γ_3 is given by*

$$f_{\gamma_3}(z) = \sum_{i=1}^{\eta(\mathbf{A}_1)}\sum_{j=1}^{\phi_i(\mathbf{A}_1)} \frac{\chi_{i,j}(\mathbf{A}_1)\,\mu_{\langle i\rangle}^{-j}}{(j-1)!} z^{j-1} e^{-\frac{z}{\mu_{\langle i\rangle}}}, \tag{13}$$

where $\mathbf{A}_1 = diag(\mu_1, \mu_2, \ldots, \mu_{N_{\rm I}})$, $\mu_{\langle i\rangle} = \frac{P_{ir}\lambda_{ir}}{\sigma^2}$ is the average interference-to-noise ratio (INR) of the ith interference signal, $\eta(\mathbf{A}_1)$ is the number of distinct diagonal elements of $\mathbf{A}_1$, $\mu_{\langle 1\rangle} > \mu_{\langle 2\rangle} > \cdots > \mu_{\langle \eta(\mathbf{A}_1)\rangle}$ are the distinct diagonal elements in decreasing order, $\phi_i(\mathbf{A}_1)$ is the multiplicity of $\mu_{\langle i\rangle}$, and $\chi_{i,j}(\mathbf{A}_1)$ is the (i,j)-th characteristic coefficient of $\mathbf{A}_1$.

Proof: The proof can be found in [17]. ■

A. Outage Probability

The outage probability is defined as the probability that the instantaneous end-to-end SINR $\gamma_{\rm D}$ falls below a predefined threshold $\gamma_{\rm th}$, mathematically, it can be expressed as

$$P_{\rm out}(\gamma_{\rm th}) = \Pr(\gamma_{\rm D} < \gamma_{\rm th}) = F_{\gamma_{\rm D}}(\gamma_{\rm th}). \tag{14}$$

Hence, to analyze the outage performance of the system, the statistical behavior of the end-to-end SINR $\gamma_{\rm D}$ is required, which is given in the following theorem.

Theorem 1. *The exact CDF of $\gamma_{\rm D}$ is given by* (15)*, where*

$$\begin{aligned} I_0(x) = &\int_0^\infty z^{j-1}(1+z)^{\frac{p+q-k+1}{2}} e^{-z\left(\frac{1}{\overline{\gamma}_1}+\frac{1}{\mu_{\langle i\rangle}}\right)} \\ &\times K_{p+q-k+1}\left(2\sqrt{\frac{x(1+x)(1+m)(1+z)}{\zeta\overline{\gamma}_1\overline{\gamma}_2}}\right)dz \end{aligned} \tag{16}$$

with $K_v(x)$ being the vth-order modified Bessel function of the second kind [36, Eq. (8.360.1)].

Proof: Starting from (7), $F_{\gamma_{\rm D}}(x)$ can be computed by

$$\begin{aligned} F_{\gamma_{\rm D}}(x) = &\int_0^x f_{\widetilde{\gamma}_2}(y)\,dy \\ &+ \int_0^\infty\int_x^\infty F_{\widetilde{\gamma}_1}\left(\frac{x(1+y)(1+z)}{y-x}\right) f_{\widetilde{\gamma}_2}(y) f_{\gamma_3}(z)\,dz. \end{aligned} \tag{17}$$

Now, substituting the CDF of $\widetilde{\gamma}_1$ and the PDFs of $\widetilde{\gamma}_2$ and γ_3 into (17), the exact expression for $F_{\gamma_{\rm D}}(x)$ can be easily obtained as (15) with the help of [36, Eq. (3.471.9)] after some simple mathematical manipulations. ■

To the best of the authors' knowledge, the integral $I_0(x)$ does not admit a closed-form expression. However, this single integral expression can be efficiently evaluated numerically, which still provides computational advantage over the Monte Carlo simulation method. Alternatively, we can use the following closed-form lower bound of the outage probability, which is tight across the entire SNR range, and becomes exact at the high SNR regime.

Corollary 1. *The outage probability of multiuser multiple antenna AF relaying systems with feedback delay and CCI is lower bounded by* (18)*.*

Proof: The key idea is to first identify an tight upper bound of the instantaneous end-to-end SINR, which is found as [18]

$$\gamma_{\rm D} \le \gamma_{\rm up} = \min\left(\frac{\widetilde{\gamma}_1}{1+\gamma_3}, \widetilde{\gamma}_2\right). \tag{19}$$

Hence, the lower bound is given by $F_{\gamma_{\rm D}}(\gamma_{\rm th}) \ge F_{\gamma_{\rm up}}(\gamma_{\rm th})$. Therefore, the remaining task is to characterize the distribution of $\gamma_{\rm up}$.

For notational convenience, we first define RV $\gamma_{13} = \frac{\widetilde{\gamma}_1}{1+\gamma_3}$. Now, due to the independence of the random variables, the CDF of $\gamma_{\rm up}$ can be expressed as

$$F_{\gamma_{\rm up}}(x) = 1 - \left[1 - F_{\gamma_{13}}(x)\right]\left[1 - F_{\widetilde{\gamma}_2}(x)\right]. \tag{20}$$

Applying the binomial expansion and exploiting [36, Eq.

$$f_{\widetilde{\gamma}_2}(y) = M \sum_{m=0}^{M-1} \frac{C_m^{M-1}(-1)^m \Phi}{(N_{\rm D}-1)!} \sum_{k=0}^{\varphi} \frac{C_k^{\varphi}\Gamma\left(N_{\rm D}+\varphi\right)\rho_2^k(1-\rho_2)^{\varphi-k}}{\Gamma\left(N_{\rm D}+k\right)\left(\overline{\gamma}_2\zeta\right)^{N_{\rm D}+k}\zeta\varphi} y^{N_{\rm D}+k-1} e^{-\frac{1+m}{\zeta\overline{\gamma}_2}y} \tag{11}$$

$$\begin{aligned} F_{\gamma_{\rm D}}(x) = 1 - 2M &\sum_{n=0}^{N_{\rm S}-1} \sum_{k=0}^{N_{\rm S}-n-1} \left(\frac{x}{\overline{\gamma}_1}\right)^k \frac{\beta_n}{k!} \sum_{m=0}^{M-1} C_m^{M-1} \frac{(-1)^m \Phi}{(N_{\rm D}-1)!} e^{-\frac{1+m}{\zeta\overline{\gamma}_2}x} \\ &\times e^{-\frac{x}{\overline{\gamma}_1}} \sum_{v=0}^{\varphi} C_v^{\varphi} \frac{\Gamma\left(N_{\rm D}+\varphi\right)\rho_2^v(1-\rho_2)^{\varphi-v}}{\Gamma\left(N_{\rm D}+v\right)\left(\overline{\gamma}_2\zeta\right)^{N_{\rm D}+v}\zeta\varphi} \sum_{q=0}^{N_{\rm D}+v-1} C_q^{N_{\rm D}+v-1} x^{N_{\rm D}+v-q-1} \\ &\times \sum_{p=0}^{k} C_p^k (1+x)^{k-p} \sum_{i=1}^{\eta(\mathbf{A}_1)} \sum_{j=1}^{\phi_i(\mathbf{A}_1)} \frac{\chi_{i,j}\left(\mathbf{A}_1\right)\mu_{\langle i\rangle}^{-j}}{(j-1)!} \left[\frac{x\left(1+x\right)\zeta\overline{\gamma}_2}{\left(1+m\right)\overline{\gamma}_1}\right]^{\frac{p+q-k+1}{2}} I_0\left(x\right) \end{aligned} \tag{15}$$

$$\begin{aligned} F_{\gamma_{\rm up}}\left(\gamma_{\rm th}\right) = 1 - &\sum_{m=0}^{M-1} \frac{C_m^{M-1}(-1)^m M\Phi}{(N_{\rm D}-1)!} \sum_{v=0}^{\varphi} \frac{C_v^{\varphi}\rho_2^v(1-\rho_2)^{\varphi-v}}{(1+m)^{N_{\rm D}+v}\zeta\varphi} \sum_{q=0}^{N_{\rm D}+v-1} \frac{\Gamma\left(N_{\rm D}+\varphi\right)}{\Gamma\left(q+1\right)} \left(\frac{1+m}{\zeta\overline{\gamma}_2}\gamma_{\rm th}\right)^q e^{-\frac{1+m}{\zeta\overline{\gamma}_2}\gamma_{\rm th}} \\ &\times e^{-\frac{\gamma_{\rm th}}{\overline{\gamma}_1}} \sum_{n=0}^{N_{\rm S}-1} \beta_n \sum_{k=0}^{N_{\rm S}-n-1} \left(\frac{\gamma_{\rm th}}{\overline{\gamma}_1}\right)^k \sum_{i=1}^{\eta(\mathbf{A}_1)} \sum_{j=1}^{\phi_i(\mathbf{A}_1)} \frac{\chi_{i,j}\left(\mathbf{A}_1\right)}{\mu_{\langle i\rangle}^j} \sum_{l=0}^{k} C_l^k \frac{(l+j-1)!}{k!\,(j-1)!} \left(\frac{\gamma_{\rm th}}{\overline{\gamma}_1} + \frac{1}{\mu_{\langle i\rangle}}\right)^{-(l+j)} \end{aligned} \tag{18}$$

(3.351.3)], the CDF of γ_{13} can be derived as

$$\begin{aligned} F_{\gamma_{13}}(x) &= \int_0^{\infty} F_{\widetilde{\gamma}_1}\left((1+z)\,x\right) f_{\gamma_3}(z)\,dz \\ &= 1 - e^{-\frac{x}{\overline{\gamma}_1}} \sum_{n=0}^{N_{\rm S}-1} \beta_n \sum_{k=0}^{N_{\rm S}-n-1} \left(\frac{x}{\overline{\gamma}_1}\right)^k \sum_{i=1}^{\eta(\mathbf{A}_1)} \sum_{j=1}^{\phi_i(\mathbf{A}_1)} \frac{1}{\mu_{\langle i\rangle}^j} \\ &\times \chi_{i,j}\left(\mathbf{A}_1\right) \sum_{l=0}^{k} C_l^k \frac{1}{k!} \frac{(l+j-1)!}{(j-1)!} \left(\frac{x}{\overline{\gamma}} + \frac{1}{\mu_{\langle i\rangle}}\right)^{-(l+j)}. \end{aligned} \tag{21}$$

Now, from the PDF presented in Lemma 2 and with the help of [36, Eq. (3.351.1)], the CDF of $\widetilde{\gamma}_2$ can be easily shown as

$$\begin{aligned} F_{\widetilde{\gamma}_2}(x) = 1 - &\sum_{m=0}^{M-1} C_m^{M-1} \frac{(-1)^m M}{(N_{\rm D}-1)!} \Phi \sum_{v=0}^{\varphi} C_v^{\varphi} \frac{\rho_2^v}{\zeta\varphi} \\ &\times \frac{(1-\rho_2)^{\varphi-v}}{(1+m)^{N_{\rm D}+v}} \sum_{q=0}^{N_{\rm D}+v-1} \frac{\Gamma\left(N_{\rm D}+\varphi\right)}{\Gamma\left(q+1\right)} \left(\frac{1+m}{\zeta\overline{\gamma}_2}x\right)^q e^{-\frac{1+m}{\zeta\overline{\gamma}_2}x}. \end{aligned} \tag{22}$$

To this end, substituting (21) and (22) into (20), the lower bound on the outage probability can be obtained as (18) after some basic mathematical manipulations. ■

To gain further insights, we now look into the high SNR regime, and derive the asymptotic expression for the outage probability, which enables the characterization of the joint effect of feedback delay, CCI, the number of antennas and users on the achievable diversity order and array gain of the system.

We find it convenient to give a separate treatment for the following two cases of interest. Case 1: interference only (perfect feedback), i.e., $\rho_1 = 1$ and $\rho_2 = 1$, and Case 2: interference and delayed feedback, i.e., $\rho_1 < 1$ and $\rho_2 < 1$.

In the high SNR regime, we assume $\overline{\gamma}_1 \to \infty$ and define $\overline{\gamma}_2 = \omega\overline{\gamma}_1$, where ω is a positive constant. Recall the definition of the diversity order in a noise-limited environment, only the asymptotically large SNR regime is of interest, hence we assume that the powers of the interferers are fixed in the analysis of diversity order [17]–[19]. We first consider the case where only CCI exists in the system, and we have the following important result.

Corollary 2. *For the system with perfect feedback, i.e., $\rho_1 = 1$ and $\rho_2 = 1$, the asymptotical approximation of the outage probability is given in* (23)*, where $\Psi\left(a, b; z\right)$ denotes the confluent hypergeometric function of the second kind [36, Eq. (9.211.4)].*

Proof: See Appendix B. ■

Corollary 2 indicates that the diversity order of the system is $\min\left\{N_{\rm S}, MN_{\rm D}\right\}$ when there is no feedback delay. Also, we can see that when $N_{\rm S} < MN_{\rm D}$, the outage performance does not depend on the number of destination users, or in another word, the contribution of multiuser diversity is negligible. This is because the performance of a two-hop communication system is limited by the weakest link. In such scenarios, the first hop becomes the bottleneck and hence the CCI has the dominating effect on the outage performance. Similarly, when $N_{\rm S} > MN_{\rm D}$, in the first hop, the source has sufficient degree of freedom to suppress the CCI, hence the performance of the second hop which is mainly determined by the available multiuser diversity, becomes the major performance limiting factor. Only for the case $N_{\rm S} = MN_{\rm D}$, both the CCI and multiuser diversity will affect the outage probability.

Next, we look at the case when the system is subjected to both the CCI and delayed feedback, and we have the following key result.

Corollary 3. *Considering both the interference and delayed feedback, i.e., $\rho_1 < 1$ and $\rho_2 < 1$, the asymptotical approximation of the outage probability is given by* (24)*.*

Proof: See Appendix C. ■

Corollary 3 shows that, in the presence of feedback delay, the achievable diversity order of the system reduces to one, regardless of the number of antennas at the source and destination as well as the number of destination users, which is

$$F_{\gamma_{\rm up}}(\gamma_{\rm th}) \approx \begin{cases} \sum_{i=1}^{\eta(\mathbf{A}_1)} \sum_{j=1}^{\phi_i(\mathbf{A}_1)} \frac{\chi_{i,j}(\mathbf{A}_1)\mu_{\langle i\rangle}^{-j}}{N_{\rm S}!} \Psi\left(j, j+N_{\rm S}+1; \mu_{\langle i\rangle}^{-1}\right)\left(\frac{\gamma_{\rm th}}{\overline{\gamma}_1}\right)^{N_{\rm S}}, & N_{\rm S} < MN_{\rm D} \\ \left[\sum_{i=1}^{\eta(\mathbf{A}_1)} \sum_{j=1}^{\phi_i(\mathbf{A}_1)} \frac{\chi_{i,j}(\mathbf{A}_1)\mu_{\langle i\rangle}^{-j}}{N_{\rm S}!} \Psi\left(j, j+N_{\rm S}+1; \mu_{\langle i\rangle}^{-1}\right) + \frac{1}{(N_{\rm D}!)^M \omega^{N_{\rm S}}}\right]\left(\frac{\gamma_{\rm th}}{\overline{\gamma}_1}\right)^{N_{\rm S}}, & N_{\rm S} = MN_{\rm D} \\ \frac{1}{(N_{\rm D}!)^M \omega^{MN_{\rm D}}}\left(\frac{\gamma_{\rm th}}{\overline{\gamma}_1}\right)^{MN_{\rm D}}, & N_{\rm S} > MN_{\rm D} \end{cases} \tag{23}$$

$$F_{\gamma_{\rm up}}(\gamma_{\rm th}) \approx \begin{cases} \left(1-\rho_1^2\right)^{N_{\rm S}-1} \sum_{i=1}^{\eta(\mathbf{A}_1)} \sum_{j=1}^{\phi_i(\mathbf{A}_1)} \frac{\chi_{i,j}(\mathbf{A}_1)}{\mu_{\langle i\rangle}^{j}} \Psi\left(j, j+2; \mu_{\langle i\rangle}^{-1}\right)\frac{\gamma_{\rm th}}{\overline{\gamma}_1}, & N_{\rm D} > 1 \\ \left[\left(1-\rho_1^2\right)^{N_{\rm S}-1} \sum_{i=1}^{\eta(\mathbf{A}_1)} \sum_{j=1}^{\phi_i(\mathbf{A}_1)} \frac{\chi_{i,j}(\mathbf{A}_1)}{\mu_{\langle i\rangle}^{j}} \Psi\left(j, j+2; \mu_{\langle i\rangle}^{-1}\right) + M\sum_{m=0}^{M-1} \frac{C_m^{M-1}(-1)^m}{\omega\zeta}\right]\frac{\gamma_{\rm th}}{\overline{\gamma}_1}, & N_{\rm D} = 1 \end{cases} \tag{24}$$

$$\begin{aligned} \overline{P}_s^{\rm low} = & \frac{a}{2} - \frac{a}{2}\sqrt{\frac{b}{\pi}} M \sum_{n=0}^{N_{\rm S}-1} \beta_n \sum_{k=0}^{N_{\rm S}-n-1} \sum_{l=0}^{k} C_l^k \sum_{i=1}^{\eta(\mathbf{A}_1)} \sum_{j=1}^{\phi_i(\mathbf{A}_1)} \frac{(l+j-1)!\chi_{i,j}(\mathbf{A}_1)\mu_{\langle i\rangle}^{l-k}}{(j-1)!k!} \\ & \times \sum_{m=0}^{M-1} \frac{C_m^{M-1}(-1)^m \Phi}{(N_{\rm D}-1)!} \sum_{v=0}^{\varphi} \frac{C_v^{\varphi}\rho_2^v(1-\rho_2)^{\varphi-v}}{(1+m)^{N_{\rm D}+v}\zeta^{\varphi}} \sum_{q=0}^{N_{\rm D}+v-1} \frac{\Gamma(N_{\rm D}+\varphi)}{\Gamma(q+1)}\left(\frac{1+m}{\zeta\overline{\gamma}_2}\right)^q \left(\frac{\overline{\gamma}_1}{\mu_{\langle i\rangle}}\right)^{q+\frac{1}{2}} \\ & \times \Gamma\left(k+q+\frac{1}{2}\right)\Psi\left(k+q+\frac{1}{2}, k+q+\frac{3}{2}-l-j, \frac{\overline{\gamma}_1}{\mu_{\langle i\rangle}}\left(b+\frac{1}{\overline{\gamma}_1}+\frac{1+m}{\overline{\gamma}_2\zeta}\right)\right) \end{aligned} \tag{27}$$

$$\overline{P}_s^{\infty} = \begin{cases} \frac{a}{b^{N_{\rm S}}N_{\rm S}!} \sum_{i=1}^{\eta(\mathbf{A}_1)} \sum_{j=1}^{\phi_i(\mathbf{A}_1)} \frac{\chi_{i,j}(\mathbf{A}_1)\Gamma(N_{\rm S}+1/2)}{2\sqrt{\pi}\mu_{\langle i\rangle}^{j}} \Psi\left(j, j+N_{\rm S}+1; \mu_{\langle i\rangle}^{-1}\right)\frac{1}{\overline{\gamma}_1^{N_{\rm S}}}, & N_{\rm S} < MN_{\rm D} \\ \frac{a\Gamma(N_{\rm S}+1/2)}{2\sqrt{\pi}b^{N_{\rm S}}} \left[\sum_{i=1}^{\eta(\mathbf{A}_1)} \sum_{j=1}^{\phi_i(\mathbf{A}_1)} \frac{\chi_{i,j}(\mathbf{A}_1)}{N_{\rm S}!\mu_{\langle i\rangle}^{j}} \Psi\left(j, j+N_{\rm S}+1; \mu_{\langle i\rangle}^{-1}\right) + \frac{1}{(N_D!)^M \omega^{MN_{\rm D}}}\right]\frac{1}{\overline{\gamma}_1^{N_{\rm S}}}, & N_{\rm S} = MN_{\rm D} \\ \frac{a\Gamma(MN_{\rm D}+1/2)}{2\sqrt{\pi}b^{N_{\rm S}}(N_D!)^M\omega^{MN_{\rm D}}}\frac{1}{\overline{\gamma}_1^{MN_{\rm D}}}, & N_{\rm S} > MN_{\rm D} \end{cases} \tag{28}$$

$$\overline{P}_s^{\infty} = \begin{cases} \frac{a}{4b}\left(1-\rho_1^2\right)^{N_{\rm S}-1} \sum_{i=1}^{\eta(\mathbf{A}_1)} \sum_{j=1}^{\phi_i(\mathbf{A}_1)} \chi_{i,j}(\mathbf{A}_1)\mu_{\langle i\rangle}^{-j} \Psi\left(j, j+2; \mu_{\langle i\rangle}^{-1}\right)\frac{1}{\overline{\gamma}_1}, & N_{\rm D} > 1 \\ \frac{a}{4b}\left[\left(1-\rho_1^2\right)^{N_{\rm S}-1} \sum_{i=1}^{\eta(\mathbf{A}_1)} \sum_{j=1}^{\phi_i(\mathbf{A}_1)} \chi_{i,j}(\mathbf{A}_1)\mu_{\langle i\rangle}^{-j} \Psi\left(j, j+2; \mu_{\langle i\rangle}^{-1}\right) + M\sum_{m=0}^{M-1} \frac{C_m^{M-1}(-1)^m}{\omega\zeta}\right]\frac{1}{\overline{\gamma}_1}, & N_{\rm D} = 1 \end{cases} \tag{29}$$

consistent with the findings reported in prior works [38], [39], hence verifying the correctness of our analysis. Nevertheless, these key parameters will affect the achievable coding gain of the system. It can be easily observed that $N_{\rm S}$ affects the outage performance through the factor $(1-\rho_1^2)$. Since $(1-\rho_1^2) < 1$, $(1-\rho_1^2)^{N_{\rm S}-1}$ is a monotonically decreasing function of $N_{\rm S}$, which suggests that increasing the number of transmit antennas is always beneficial. Moreover, the degree of improvement is closely related to the level of imperfection of the CSI. For instance, increasing $N_{\rm S}$ by one when $N_{\rm D} > 1$, the outage probability is reduced by a factor of $1-\rho_1^2$, which is insignificant when ρ_1 is small and prominent when ρ_1 is large, indicating that the impact of $N_{\rm S}$ is more pronounced when the feedback delay is small.

B. Symbol Error Rate

In this section, we analyze the average SER of the system, which is another important metric to quantify the performance of wireless communication systems. For a broad variety of modulations, the average SER can be expressed (or approximated) as

$$\overline{P}_s = a\mathrm{E}\left[Q\left(\sqrt{2b\gamma_{\rm D}}\right)\right], \tag{25}$$

where $Q(x) = 1/\sqrt{2\pi}\int_x^{\infty} e^{-y^2/2}dy$ is the the Gaussian Q-function, and a and b are modulation parameters. For instance, binary phase-shift keying (BPSK) with $a=1$ and $b=1$, and M-ary pulse amplitude modulation (PAM) with $a = 2(M-1)/M$ and $b = 3/\left(M^2-1\right)$, and a tight approximation for M-PSK with $a=2$ and $b=\sin^2(\pi/M)$ [40]. After integrating by parts, the average SER can be alternatively represented by [41]

$$\overline{P}_s = \frac{a}{2}\sqrt{\frac{b}{\pi}}\int_0^{\infty}\frac{e^{-bx}}{\sqrt{x}}F_{\gamma_{\rm D}}(x)\,dx, \tag{26}$$

Due to the fact that the CDF of the SINR $\gamma_{\rm D}$ admits no closed-form, we resort to the SINR upper bound $\gamma_{\rm up}$ to derive the average SER and we obtain the following key result.

Corollary 4. *The average SER of multiuser multiple antenna AF relaying systems with feedback delay and CCI is lower bounded by* (27).

Proof: See Appendix D. ■

Corollary 4 presents an analytical expression for the average SER of the system, and it applies to the generic scenario with feedback delay, arbitrary number of antennas, arbitrary number of interferers and arbitrary number of users at any SINRs. Moreover, the expression only involves standard functions which allows for fast evaluation in popular mathematical software such as Matlab, thereby providing an efficient means to access the average SER of the system.

In order to get more insights into how the key system parameters such as number of antennas $N_{\rm S}$ and $N_{\rm D}$, number of users M, interference, and correlation coefficients ρ_1 and ρ_2 affect the average SER of the system, we now present simple expressions of the average SER in the high SNR regime, from which the diversity order and coding gain can be easily analyzed. Similar to the outage analysis part, we consider two asymptotic SER cases depending on the values of ρ_1 and ρ_2.

Corollary 5. *With only CCI, i.e., $\rho_1 = 1$ and $\rho_2 = 1$, the average SER for multiuser multiple antenna AF relaying systems in high SNR can be approximated as* (28).

Proof: Substituting the asymptotic CDF expression presented in (23) into (27), the desired result can be obtained with the help of [36, Eq. (3.351.3)]. ■

Corollary 6. *With both the CCI and delayed feedback, i.e., $\rho_1 < 1$ and $\rho_2 < 1$, the average SER for multiuser multiple antenna AF relaying systems in high SNR can be approximated as* (29).

Proof: Substituting the asymptotic CDF expression presented in (24) into (27) and utilizing [36, Eq. (3.351.3)], the desired result can be obtained after some algebraic manipulations. ■

From the above two corollaries, it is easy to see that the diversity order achieved by the system is $\min\{N_{\rm S}, MN_{\rm D}\}$ when there is no feedback delay. While for the case with feedback delay, the achievable diversity order reduces to one. Moreover, the results indicate that the CCI does not reduce the achievable diversity order, it degrades the performance of the system by affecting the coding gain of the system.

C. Ergodic Capacity

The ergodic capacity can be defined as the expected value of the instantaneous mutual information of the end-to-end SINR $\gamma_{\rm D}$, which can be represented as

$$C = \frac{1}{2}\mathrm{E}\left[\log_2\left(1+\gamma_{\rm D}\right)\right], \qquad (30)$$

where the factor $1/2$ accounts for the fact that the entire communication takes place in two time slots. Unfortunately, obtaining a closed-form solution to (30) is in general intractable due to the presence of the nonlinear $\log_2(\cdot)$ function. On this basis, we hereafter seek to find tight lower and upper bound for the ergodic capacity using some tractable statistical tools.

At this point, it is worth pointing out that the ergodic capacity of multiple antenna AF relaying systems has been investigated in [15], which, nevertheless assumes a single user system with an interference-limited relay. On the contrary, here we address the more practical multiuser system with both interference and AWGN noise at the relay. Hence, our analysis could be regarded as an important extension of [15]. Moreover, the multiuser scenario gives rise to the problem of the coupled effect of the antenna diversity and multiuser diversity on the ergodic capacity performance, which does not appear in the single user system studied in [15] and will be examined here.

We start with the following upper bound.

Theorem 2. *The ergodic capacity of multiuser multiple antenna relaying networks with CCI and feedback delay is upper bounded by* (31)*, where $G^{1,1,1,1,1}_{1,[1:1],0,[1:1]}[\cdot]$ is the generalized Meijer's G-function of two variables and $G^{1,1}_{1,1}[\cdot]$ is the Meijer's G-function, α_1, α_3 and α_2 are given in* (73), (74), *and* (75), *respectively.*

Proof: See Appendix E. ■

Please note that the generalized Meijer's G-function of two variables is a build-in function in Mathematica, hence can be directly computed. Alternatively, an efficient approach developed in [41, Table II] could be used to evaluate the expression. Now, we turn our attention to the ergodic capacity lower bound, and we have the following key result.

Theorem 3. *The ergodic capacity of multiuser multiple antenna relaying networks with CCI and feedback delay is lower bounded by* (32)*, where ϑ_1, ϑ_3 and ϑ_2 are given in* (78), (79), *and* (80)*, respectively.*

Proof: See Appendix F. ■

It is worth highlighting that Theorem 2 and Theorem 3 provide general expressions of the lower and upper capacity bounds, which are valid for the system with arbitrary number of antennas, users and interferers. More importantly, the derived bounds remain sufficiently tight across the entire range of SNRs as will be demonstrated in Section V. Hence, these new analytical capacity bounds provide an efficient means to characterize the impact of key system parameters such as feedback delay, number of antennas and users, and CCI on the ergodic capacity of the system, without resorting to the time-consuming Monte Carlo simulations.

IV. Optimum Power Allocation

In this section, we propose optimum power allocation schemes minimizing the asymptotic average SER with/without feedback delay. Specifically, we consider the scenario that the total transmit power between the source and the relay is fixed, i.e., $P_s + P_r = P_t$. Let us define ε as the power allocation factor such that $P_s = \varepsilon P_t$ and $P_r = (1-\varepsilon)P_t$.

A. Optimum Power Allocation with Perfect Feedback

As can be readily observed from (28), more power should be allocated to the source to suppress the interferers at the relay when $N_{\rm S} < MN_{\rm D}$. In contrast, the relay node should be allocated more power to alleviate the channel fading of second-hop links when $N_{\rm S} > MN_{\rm D}$. On the other hand, the case $N_{\rm S} = MN_{\rm D}$ requires a bit more careful consideration. The corresponding optimization problem can be formulated as

$$\varepsilon_1^* = \arg\min_{\varepsilon_1} \overline{P}_s^{\infty}(\varepsilon_1) \quad \text{subject to} : 0 < \varepsilon_1 < 1, \qquad (33)$$

$$C_u = \frac{\overline{\gamma}_1}{2\ln 2}\sum_{n=0}^{N_{\rm S}-1}\beta_n\sum_{k=0}^{N_{\rm S}-n-1}\sum_{i=1}^{\eta(\mathbf{A}_1)}\sum_{j=1}^{\phi_i(\mathbf{A}_1)}\sum_{l=0}^{k}C_l^k\frac{\chi_{i,j}\left(\mathbf{A}_1\right)\mu_{\langle i\rangle}^l}{k!\,(j-1)!}G_{1,[1:1],0,[1:1]}^{1,1,1,1,1}\left[\mu_{\langle i\rangle},\overline{\gamma}_1\left|\begin{matrix}k+1;1-l-j;0\\--;0;0\end{matrix}\right.\right]$$
$$+\frac{M}{2}\sum_{m=0}^{M-1}\frac{C_m^{M-1}(-1)^m\Phi}{(N_{\rm D}-1)!}\sum_{k=0}^{\varphi}\frac{C_k^{\varphi}\Gamma\left(N_{\rm D}+\varphi\right)\rho_2^k(1-\rho_2)^{\varphi-k}}{\Gamma\left(N_{\rm D}+k\right)(1+m)^{N_{\rm D}+k}\zeta^{\varphi}}G_{3,2}^{1,3}\left[\frac{\zeta\overline{\gamma}_2}{1+m}\left|\begin{matrix}1-N_{\rm D}-k,1,1\\1,0\end{matrix}\right.\right]$$
$$-\frac{1}{2}\log_2\left(1+e^{\alpha_1-\alpha_3}+e^{\alpha_2}\right) \tag{31}$$

$$C_l = \frac{\overline{\gamma}_1}{2\ln 2}\sum_{n=0}^{N_{\rm S}-1}\beta_n\sum_{k=0}^{N_{\rm S}-n-1}\sum_{i=1}^{\eta(\mathbf{A}_1)}\sum_{j=1}^{\phi_i(\mathbf{A}_1)}\sum_{l=0}^{k}C_l^k\frac{\chi_{i,j}\left(\mathbf{A}_1\right)\mu_{\langle i\rangle}^l}{k!\,(j-1)!}G_{1,[1:1],0,[1:1]}^{1,1,1,1,1}\left[\mu_{\langle i\rangle},\overline{\gamma}_1\left|\begin{matrix}k+1;1-l-j;0\\--;0;0\end{matrix}\right.\right]$$
$$+\frac{M}{2}\sum_{m=0}^{M-1}\frac{C_m^{M-1}(-1)^m\Phi}{(N_{\rm D}-1)!}\sum_{k=0}^{\varphi}\frac{C_k^{\varphi}\Gamma\left(N_{\rm D}+\varphi\right)\rho_2^k(1-\rho_2)^{\varphi-k}}{\Gamma\left(N_{\rm D}+k\right)(1+m)^{N_{\rm D}+k}\zeta^{\varphi}}G_{3,2}^{1,3}\left[\frac{\zeta\overline{\gamma}_2}{1+m}\left|\begin{matrix}1-N_{\rm D}-k,1,1\\1,0\end{matrix}\right.\right]$$
$$-\frac{1}{2}\log_2\left(1+\vartheta_1-\vartheta_3+\vartheta_2\right) \tag{32}$$

$$\overline{P}_s^{\infty}\left(\varepsilon_1\right)=\frac{a\Gamma\left(N_{\rm S}+1/2\right)}{2\sqrt{\pi}b^{N_{\rm S}}P_t^{N_{\rm S}}}\left[\sum_{i=1}^{\eta(\mathbf{A}_1)}\sum_{j=1}^{\phi_i(\mathbf{A}_1)}\frac{\chi_{i,j}\left(\mathbf{A}_1\right)}{N_{\rm s}!\mu_{\langle i\rangle}^j}\left(\frac{\sigma^2}{\lambda_1\varepsilon_1}\right)^{N_{\rm S}}\Psi\left(j,j+N_{\rm s}+1;\mu_{\langle i\rangle}^{-1}\right)+\frac{1}{\left(N_D!\right)^M}\left(\frac{\sigma^2}{\lambda_2\left(1-\varepsilon_2\right)}\right)^{N_{\rm S}}\right] \tag{34}$$

$$\overline{P}_s^{\infty}\left(\varepsilon_2\right)=\frac{a\Gamma\left(3/2\right)\sigma^2}{2\sqrt{\pi}bP_t}\left[\left(1-\rho_1^2\right)^{N_{\rm s}-1}\sum_{i=1}^{\eta(\mathbf{A}_1)}\sum_{j=1}^{\phi_i(\mathbf{A}_1)}\frac{\chi_{i,j}\left(\mathbf{A}_1\right)\Psi\left(j,j+2;\mu_{\langle i\rangle}^{-1}\right)}{\mu_{\langle i\rangle}^j\lambda_1\varepsilon_2}+\sum_{m=0}^{M-1}C_m^{M-1}\frac{(-1)^mM}{\lambda_2\left(1-\varepsilon_2\right)\zeta}\right] \tag{38}$$

where $\overline{P}_s^{\infty}\left(\varepsilon_1\right)$ is given by (34).

To this end, taking the second derivative of $\overline{P}_s^{\infty}\left(\varepsilon_1\right)$ with respect to ε_1, it can be shown that $\partial^2\overline{P}_s^{\infty}\left(\varepsilon_1\right)\Big/\partial\varepsilon_1^2$ is strictly positive in the interval $(0,1)$, which implies that the objective function is a strictly convex function of ε_1 in the interval $(0,1)$. Therefore, taking the first order derivative of $\overline{P}_s^{\infty}\left(\varepsilon_1\right)$ with respect to ε_1 and setting it to zero, the optimal ε_1 can be obtained. After some straightforward yet tedious algebraic manipulations, we have

$$\varepsilon_1^*=\frac{\kappa_1^{\frac{1}{N_{\rm S}+1}}}{1+\kappa_1^{\frac{1}{N_{\rm S}+1}}}, \tag{35}$$

where

$$\kappa_1=\frac{\left(N_D!\right)^M}{N_{\rm s}!}\left(\frac{\lambda_2}{\lambda_1}\right)^{N_{\rm S}}\sum_{i=1}^{\eta(\mathbf{A}_1)}\sum_{j=1}^{\phi_i(\mathbf{A}_1)}\frac{\chi_{i,j}\left(\mathbf{A}_1\right)}{\mu_{\langle i\rangle}^j}\Psi\left(j,j+N_{\rm s}+1;\mu_{\langle i\rangle}^{-1}\right). \tag{36}$$

B. Optimum Power Allocation with Delayed Feedback

Similarly, for the case $\rho_1<1$ and $\rho_2<1$, more power should be allocated to the source when each destination node has more than a single antenna. On the other hand, when the destination is equipped with a single antenna, the optimal power allocation problem can be formulated as

$$\varepsilon_2^*=\arg\min_{\varepsilon_2}\overline{P}_s^{\infty}\left(\varepsilon_2\right)\quad\text{subject to}:0<\varepsilon_2<1, \tag{37}$$

where $\overline{P}_s^{\infty}\left(\varepsilon_2\right)$ is given by (38).

After some algebraic manipulations, it can be proven that the second derivative of $\overline{P}_s^{\infty}\left(\varepsilon_2\right)$ with respect to ε_2 is strictly positive, which implies that the objective function is a strictly convex function of ε_2. Setting the first derivative of the objective function with respective to ε_2 to zero, the optimal power allocation factor can be derived as

$$\varepsilon_2^*=\frac{\sqrt{\kappa_2/\kappa_3}}{1+\sqrt{\kappa_2/\kappa_3}}, \tag{39}$$

where

$$\kappa_2=\frac{\left(1-\rho_1^2\right)^{N_{\rm s}-1}}{\lambda_1}\sum_{i=1}^{\eta(\mathbf{A}_1)}\sum_{j=1}^{\phi_i(\mathbf{A}_1)}\frac{\chi_{i,j}\left(\mathbf{A}_1\right)}{\mu_{\langle i\rangle}^j}\Psi\left(j,j+2;\mu_{\langle i\rangle}^{-1}\right), \tag{40}$$

$$\kappa_3=M\sum_{m=0}^{M-1}C_m^{M-1}(-1)^m(\lambda_2\varsigma)^{-1}. \tag{41}$$

V. Numerical Results

In this section, we conduct numerical simulations to validate the analytical results presented in the previous section. Without loss of generality, we define the SNR as $\overline{\gamma}_1$, and assume that $\overline{\gamma}_1=\overline{\gamma}_2$. Also, although our analytical results apply to arbitrary number of interferers with arbitrary interference power distribution, here we limit the simulation to the case where there are three interferers, i.e., $N_{\rm I}=3$, with average INR $\mu_i=5{\rm dB}$. Finally, we set the outage threshold $\gamma_{\rm th}=5{\rm dB}$.

Fig. 2 shows the outage probability of multiuser multiple antenna AF relaying networks for different ρ_1 and ρ_2. It is

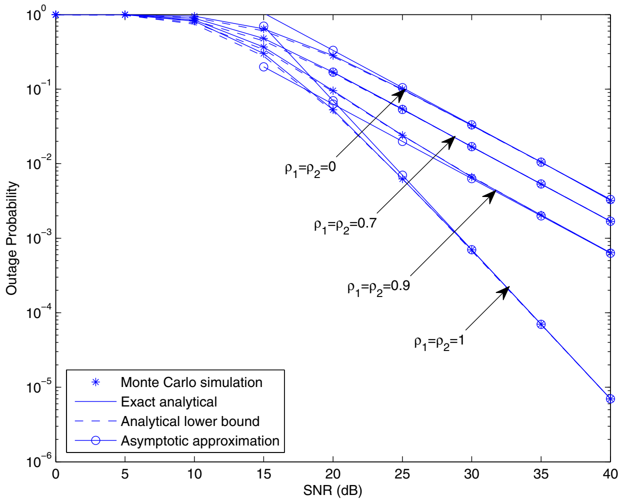

Fig. 2. The outage probability under different values of correlation $\rho_1 = \rho_2$ for $N_{\mathrm{S}} = 2$, $N_{\mathrm{D}} = 2$, $M = 2$ and $N_{\mathrm{I}} = 3$.

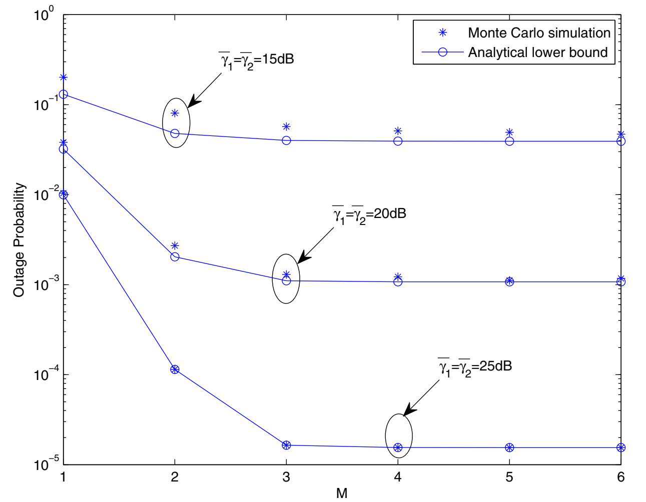

Fig. 4. Impact of numbers of user on the outage probability under perfect feedback for $N_{\mathrm{S}} = 4$, $N_{\mathrm{D}} = 1$ and $N_{\mathrm{I}} = 3$.

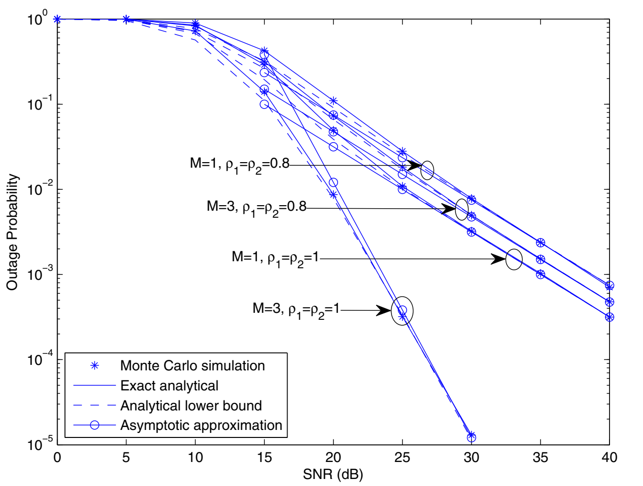

Fig. 3. The outage probability under different values of user M for $N_{\mathrm{S}} = 3$, $N_{\mathrm{D}} = 1$ and $N_{\mathrm{I}} = 3$.

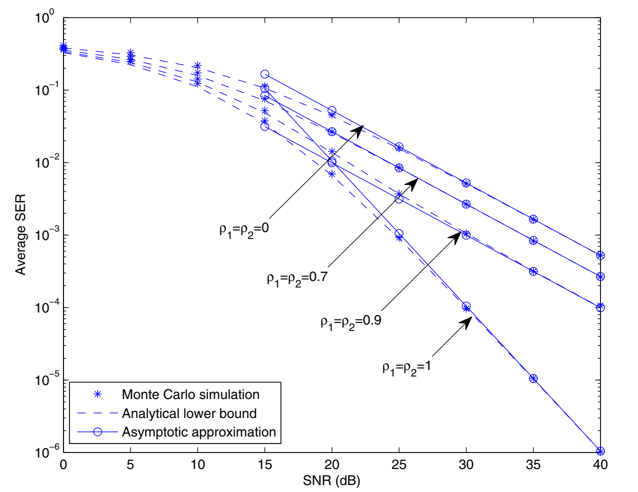

Fig. 5. The average SER under different values of correlation $\rho_1 = \rho_2$ for $N_{\mathrm{S}} = 2$, $N_{\mathrm{D}} = 2$, $M = 2$ and $N_{\mathrm{I}} = 3$.

observed that the analytical results are in exact agreement with the Monte Carlo simulation results, and the outage lower bound is sufficiently tight across the entire SNR range of interest, while the high SNR curves work quite well even at moderate SNRs (i.e., $\overline{\gamma}_1 = 20\mathrm{dB}$). In addition, we can see that, only if $\rho_1 = \rho_2 = 1$, the full diversity order can be achieved. As long as $\rho_1 < 1$ or $\rho_2 < 1$, the achievable diversity order reduces to one. Moreover, the larger the feedback delay, the poorer the outage performance.

Fig. 3 examines the impact of the number of users on the outage performance. We observe that, when $\rho_1 = \rho_2 = 0.8$, increasing the number of users M has marginal impact on the outage performance. This can be explained by the fact that only diversity order of one is achieved for the system under delayed feedback case, hence, increasing M does not provide additional diversity order for the system. In contrast, we see a significant outage improvement with the increase of the number of users M when $\rho_1 = \rho_2 = 1$. This is because more multiuser diversity can be obtained by increasing M under the perfect feedback case when $N_{\mathrm{S}} > MN_{\mathrm{D}}$. However, when $N_{\mathrm{S}} < MN_{\mathrm{D}}$, the diversity order of the system is limited to N_{S}. In such case, increasing M beyond N_{S} does not provide an additional diversity gain. This observation is demonstrated in Fig. 4.

Fig. 5 presents the average SER of system with quadrature phase shift keying (QPSK) modulation ($a = 2, b = 0.5$). As shown in the figure, the average SER lower bound is very tight with the Monte carlo simulations in the high SNR regime, which verifies the correctness of our analysis. Moreover, the asymptotic SER curves are plotted to obtain direct insights about the diversity order and array gain of the system under perfect feedback and delayed feedback, respectively. Just as in the outage probability case, we observe that high feedback delay, i.e., small ρ_1 and ρ_2, significantly degrades the error performance of the system.

Fig. 6 examines the impact of number of users on the average SER of multiuser multiple antenna relaying systems for perfect feedback and delayed feedback cases. Similar to the outage probability case, we observe that increasing M has no impact on the average error performance in the case of delayed feedback, while the average SER is significantly

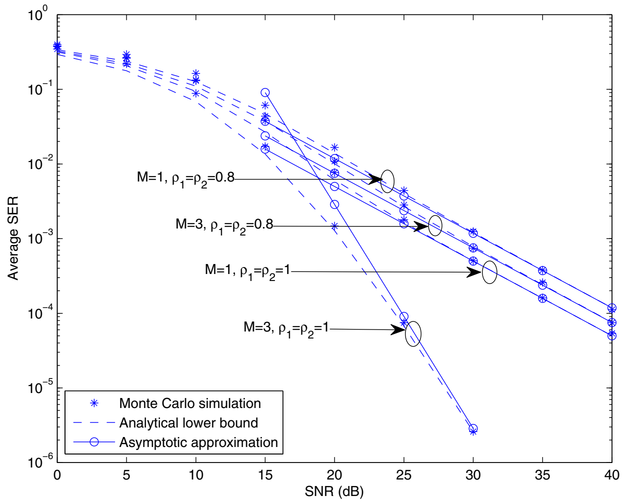

Fig. 6. The average SER under different values of user M for $N_{\mathrm{S}} = 3$, $N_{\mathrm{D}} = 1$ and $N_{\mathrm{I}} = 3$.

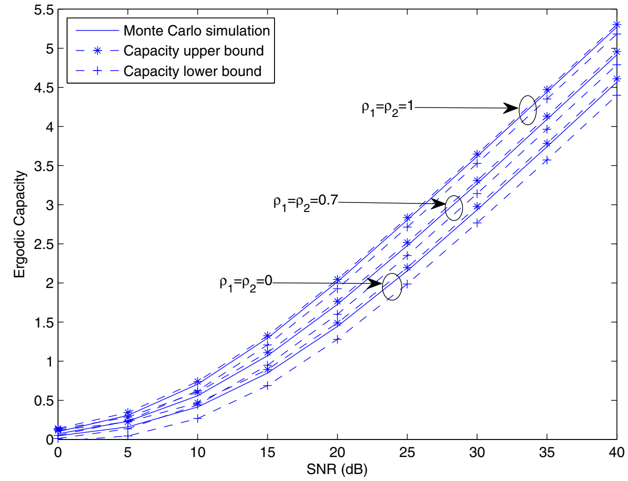

Fig. 8. Impact of feedback delay on the ergodic capacity for $N_{\mathrm{S}} = 2$, $N_{\mathrm{D}} = 2$, $M = 2$ and $N_{\mathrm{I}} = 3$.

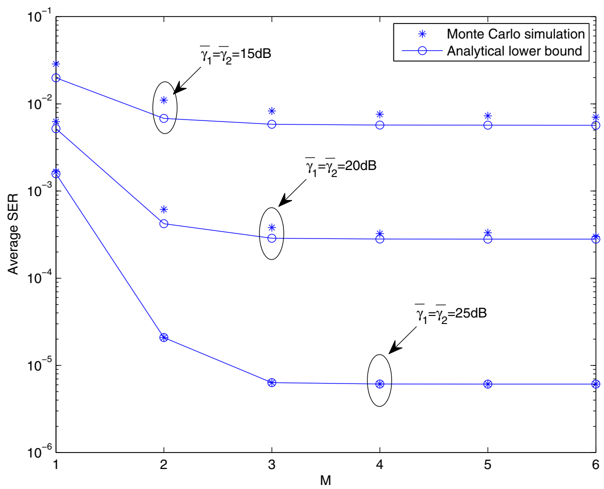

Fig. 7. Impact of numbers of user on the average SER under perfect feedback for $N_{\mathrm{S}} = 4$, $N_{\mathrm{D}} = 1$ and $N_{\mathrm{I}} = 3$.

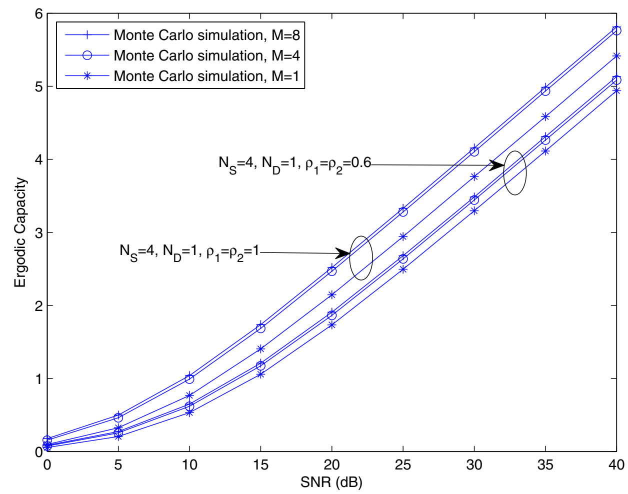

Fig. 9. Impact of numbers of user on the ergodic capacity for $N_{\mathrm{S}} = 4$, $N_{\mathrm{D}} = 1$, and $N_{\mathrm{I}} = 3$.

improved by increasing numbers of user due to the increase in multiuser diversity under the perfect feedback case. However, as can be observed in Fig. 7, such performance gain gradually diminishes when M becomes larger due to the limitation of the full diversity order to N_{S}, which means opportunistic scheduling will not improve the channel quality of the first hop, resulting in a less noticeable performance improvement.

Fig. 8 illustrates the ergodic capacity of the system with different ρ_1 and ρ_2. As can be readily observed, the proposed lower and upper bounds are generally quite tight across the entire SNR range. In particular, the capacity upper bound overlaps with the Monte Carlo simulation results in the high SNR regime. In addition, we also observe the intuitive result that the ergodic capacity of the system improves when feedback delay is reduced, i.e., when ρ_1 and ρ_2 increase from 0 to 1.

In Fig. 9, the impact of number of users on the ergodic capacity of the system is studied. We see that, in the case of delayed feedback, opportunistic scheduling only provides marginal ergodic capacity improvement when the number of users M increases from 1 to 8. In contrast, ergodic capacity enhancement due to multiuser diversity is much more pronounced in the case of perfect feedback. Moreover, when M becomes larger than N_{S}, the additional capacity gains diminish quickly, since in such case, the performance will be primarily limited by performance of the first hop.

Fig. 10 studies the impact of power allocation on the average SER of the system. It can be observed from the figure that the proposed optimal power allocation scheme improves the SER performance compared with the uniform power allocation scheme. However, the SER improvement is much more significant for the case with perfect feedback.

VI. Conclusions

In this paper, we have investigated the performance of multiuser multiple antenna AF relaying systems in the presence of CCI and feedback delay. We have derived closed-form expressions for the outage probability and average SER of the system, which provide fast and efficient means to evaluate the performance of the system. Moreover, simple and informative high SNR approximations for the outage probability and average SER were derived, which enables us

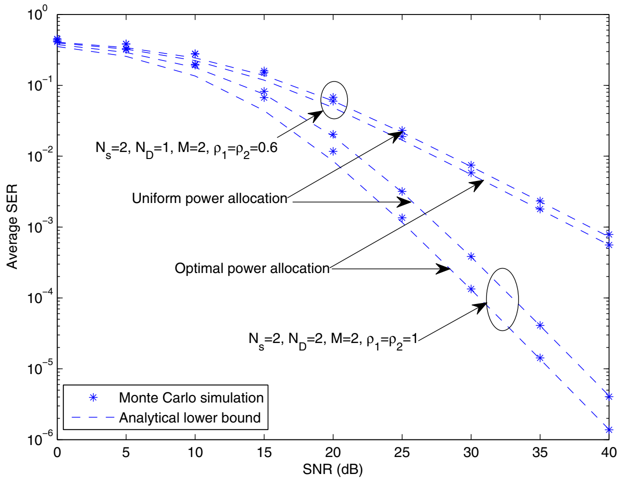

Fig. 10. The average SER of multiuser multiple antenna relaying systems with $N_{\rm I}=3$: the optimal power allocation vs. the equal power allocation.

to gain further insights into the impact of key parameters such as CCI, correlation coefficients ρ_1 and ρ_2, antenna numbers $N_{\rm S}$ and $N_{\rm D}$ and user number M on the system performance. Furthermore, two novel capacity bounds were proposed, which were demonstrated to be very tight in the entire SNR regime. Finally, we derived closed-form solution for the optimum power allocation scheme to minimize the average SER of the system. The findings of the paper suggest that the feedback delay results in a loss of spatial diversity and multiuser diversity. Specifically, it was demonstrated that the diversity order reduces to one in the presence of feedback delay regardless of the number of antennas and users.

Appendix A
Proof of Lemma 2

According to [32], the PDF of $\widetilde{\gamma}_2$ is given by

$$f_{\widetilde{\gamma}_2}(x)=\int_0^\infty f_{\widetilde{\gamma}_2|\gamma_2}(x|\,y)\,f_{\gamma_2}(y)\,dy, \tag{42}$$

where

$$f_{\widetilde{\gamma}_2|\gamma_2}(x|\,y)=\frac{f_{\widetilde{\gamma}_{2m},\gamma_{2m}}(x,y)}{f_{\gamma_{2m}}(y)} \tag{43}$$

with $f_{\widetilde{\gamma}_{2m},\gamma_{2m}}(x,y)$ being the joint PDF of $\widetilde{\gamma}_{2m}$ and γ_{2m}. Its PDF has been reported in [35]

$$f_{\widetilde{\gamma}_{2m},\gamma_{2m}}(x,y)=\frac{1}{\overline{\gamma}_2^{N_{\rm D}+1}}\frac{(xy/\rho_2)^{\frac{N_{\rm D}-1}{2}}}{(N_{\rm D}-1)!\,(1-\rho_2)}\times e^{-\frac{x+y}{(1-\rho_2)\overline{\gamma}_2}}I_{N_{\rm D}-1}\left(\frac{2\sqrt{\rho_2 xy}}{(1-\rho_2)\,\overline{\gamma}_2}\right), \tag{44}$$

where $I_v(\cdot)$ is the vth-order modified Bessel function of the first kind [36, Eq. (8.406.1)]. The PDF of γ_{2m} is given as

$$f_{\gamma_{2m}}(y)=\frac{y^{N_{\rm D}-1}}{(N_{\rm D}-1)!\overline{\gamma}_2^{N_{\rm D}}}e^{-\frac{y}{\overline{\gamma}_2}}. \tag{45}$$

With the help of [36, Eq. (3.351.1)], the corresponding CDF of γ_{2m} can be derived as

$$F_{\gamma_{2m}}(y)=1-e^{-\frac{y}{\overline{\gamma}_2}}\sum_{k=0}^{N_{\rm D}-1}\frac{1}{k!}\left(\frac{y}{\overline{\gamma}_2}\right)^k. \tag{46}$$

According to (6), the PDF of γ_2 can be derived as

$$f_{\gamma_2}(y)=M[F_{\gamma_{2m}}(y)]^{M-1}f_{\gamma_{2m}}(y). \tag{47}$$

Substituting (45) and (46) into (47) and utilizing the multinomial theorem, we have

$$f_{\gamma_2}(y)=M\sum_{m=0}^{M-1}C_m^{M-1}\frac{(-1)^m\Phi}{(N_{\rm D}-1)!}\frac{y^{N_{\rm D}+\varphi-1}}{\overline{\gamma}_2^{N_{\rm D}+\varphi}}e^{-\frac{1+m}{\overline{\gamma}_2}y}. \tag{48}$$

Then, by substituting (43) and (48) into (42), we have

$$f_{\widetilde{\gamma}_2}(x)=\left(\frac{x}{\rho_2}\right)^{\frac{N_{\rm D}-1}{2}}\frac{e^{-\frac{x}{(1-\rho_2)\overline{\gamma}_2}}}{(1-\rho_2)}\sum_{m=0}^{M-1}\frac{MC_m^{M-1}(-1)^m\Phi}{(N_{\rm D}-1)!\overline{\gamma}_2^{N_{\rm D}+\varphi+1}}\times\underbrace{\int_0^\infty y^{\frac{N_{\rm D}-1}{2}+\varphi}e^{-y\left(\frac{1}{(1-\rho_2)\overline{\gamma}_2}+\frac{m}{\overline{\gamma}_2}\right)}I_{N_{\rm D}-1}\left(\frac{2\sqrt{\rho_2 xy}}{(1-\rho_2)\,\overline{\gamma}_2}\right)dy}_{\Delta_1}. \tag{49}$$

With the help of [36, Eq. (6.643.2)], the integral Δ_1 can be obtained as

$$\Delta_1=\frac{\Gamma(N_{\rm D}+\varphi)}{\Gamma(N_{\rm D})}\frac{(1-\rho_2)\,\overline{\gamma}_2}{\sqrt{\rho_2 x}}\left[\frac{1+(1-\rho_2)\,m}{(1-\rho_2)\,\overline{\gamma}_2}\right]^{\frac{N_{\rm D}}{2}+\varphi}\times e^{\frac{\rho_2 x}{2[1+(1-\rho_2)m]\overline{\gamma}_2}}M_{-\frac{N_{\rm D}}{2}-\varphi,\frac{N_{\rm D}-1}{2}}\left(\frac{\rho_2 x}{[1+(1-\rho_2)\,m]\,\overline{\gamma}_2}\right), \tag{50}$$

where $M_{a,b}(\cdot)$ is the Whittaker-M function [36, Eq. (9.220.2)]. Furthermore, we resort to [14, Eq. (60)] to re-express the Whittaker-M function in terms of the polynomial as

$$M_{a,b}(z)=e^{\frac{z}{2}}\sum_{k=0}^{-b-a-\frac{1}{2}}C_k^{-b-a-\frac{1}{2}}z^{b+k+\frac{1}{2}}\frac{\Gamma(2b+1)}{\Gamma(2b+k+1)} \tag{51}$$

To this end, with the help of (51), the desired PDF of $\widetilde{\gamma}_2$ is given by (11).

Appendix B
Proof of Corollary 2

When there is no feedback delay, the PDF of $\widetilde{\gamma}_1$ can be simplified as

$$f_{\widetilde{\gamma}_1}(x)=\frac{x^{N_{\rm S}-1}}{(N_{\rm S}-1)!\overline{\gamma}_1^{N_{\rm S}}}e^{-\frac{x}{\overline{\gamma}_1}}. \tag{52}$$

In the high SNR regime, we have $\overline{\gamma}_1,\overline{\gamma}_2\to\infty$. Utilizing the Maclaurin series expansion of the exponential function, the PDF of $\widetilde{\gamma}_1$ can be approximated as

$$f_{\widetilde{\gamma}_1}(x)\approx\frac{x^{N_{\rm S}-1}}{(N_{\rm S}-1)!\overline{\gamma}_1^{N_{\rm S}}}. \tag{53}$$

Then, by integrating the PDF of $\widetilde{\gamma}_1$, we have

$$F_{\widetilde{\gamma}_1}(x)\approx\frac{1}{N_{\rm S}!}\left(\frac{x}{\overline{\gamma}_1}\right)^{N_{\rm S}}. \tag{54}$$

Hence, substituting (54) into (20), the CDF of γ_{13} can be computed as

$$F_{\gamma_{13}}(x) \approx \sum_{i=1}^{\eta(\mathbf{A}_1)} \sum_{j=1}^{\phi_i(\mathbf{A}_1)} \frac{\chi_{i,j}(\mathbf{A}_1)\,\mu_{\langle i\rangle}^{-j}}{\Gamma(N_{\mathrm{s}}+1)} \times \Psi\left(j, j+N_{\mathrm{s}}+1; \frac{1}{\mu_{\langle i\rangle}}\right)\left(\frac{x}{\overline{\gamma}_1}\right)^{N_{\mathrm{s}}}. \quad (55)$$

Similarly, we can rewrite the PDF of γ_{2m} in the high SNR regime as

$$f_{\gamma_{2m}}(x) \approx \frac{x^{N_{\mathrm{D}}-1}}{(N_{\mathrm{D}}-1)!\,\overline{\gamma}_2^{N_{\mathrm{D}}}}. \quad (56)$$

And the corresponding CDF of γ_{2m} in the high SNR regime is given by

$$F_{\widetilde{\gamma}_{2m}}(x) \approx \frac{1}{N_{\mathrm{D}}!}\left(\frac{x}{\overline{\gamma}_2}\right)^{N_{\mathrm{D}}}. \quad (57)$$

Then, based on the principle of opportunistic scheduling, we have

$$F_{\gamma_2}(x) \approx \frac{x^{MN_{\mathrm{D}}}}{(N_{\mathrm{D}}!)^M\,\overline{\gamma}_2^{MN_{\mathrm{D}}}}. \quad (58)$$

To this end, by employing (55) and (58) in [45, Eqs. (A.09) and (A.10)], the asymptotic outage probability result can be derived as (23) after some mathematical manipulations.

Appendix C
Proof of Corollary 3

At the high SNR regime, from (10), the CDF of $\widetilde{\gamma}_1$ can be easily approximated as

$$F_{\widetilde{\gamma}_1}(x) \approx \left(1-\rho_1^2\right)^{N_{\mathrm{S}}-1}\frac{x}{\overline{\gamma}_1}. \quad (59)$$

Hence, the CDF of RV γ_{13} can be derived as

$$F_{\gamma_{13}}(x) \approx \left(1-\rho_1^2\right)^{N_{\mathrm{s}}-1} \sum_{i=1}^{\eta(\mathbf{A}_1)} \sum_{j=1}^{\phi_i(\mathbf{A}_1)} \frac{1}{\mu_{\langle i\rangle}^{j}} \times \chi_{i,j}(\mathbf{A}_1)\,\Psi\left(j, j+2; \frac{1}{\mu_{\langle i\rangle}}\right). \quad (60)$$

On the other hand, the PDF of $\widetilde{\gamma}_2$ can be approximated as

$$f_{\widetilde{\gamma}_2}(x) \approx \sum_{m=0}^{M-1} \frac{C_m^{M-1}(-1)^m M\Phi(1-\rho_2)^{\varphi}\Gamma(N_{\mathrm{D}}+\varphi)}{(N_{\mathrm{D}}-1)!\,\zeta^{N_{\mathrm{D}}+\varphi}\Gamma(N_{\mathrm{D}})\,\overline{\gamma}_2^{N_{\mathrm{D}}}} x^{N_{\mathrm{D}}-1}. \quad (61)$$

Correspondingly, the CDF of $\widetilde{\gamma}_2$ can be computed as

$$F_{\widetilde{\gamma}_2}(x) \approx M\sum_{m=0}^{M-1} C_m^{M-1}\frac{(-1)^m\Phi\Gamma(N_{\mathrm{D}}+\varphi)(1-\rho_2)^{\varphi}}{\Gamma(N_{\mathrm{D}})\Gamma(N_{\mathrm{D}}+1)\,\zeta^{N_{\mathrm{D}}+\varphi}}\frac{x^{N_{\mathrm{D}}}}{\overline{\gamma}_2^{N_{\mathrm{D}}}}. \quad (62)$$

To this end, pulling everything together yields the desired result as shown in (24).

Appendix D
Proof of Corollary 4

Substituting (18) into (26), the lower bound of the average SER can be expressed as (63). With the help of [36, Eq. (3.361.2)], we have $I_1 = \sqrt{\frac{\pi}{b}}$. Then, making a change of variable $t = \frac{\mu_{\langle i\rangle}x}{\overline{\gamma}_1}$ and exploiting the equation [36, Eq. (9.211.4)], the integral I_2 can be derived as (64). Now, substituting the integral I_1 and I_2 into (63), we have the lower bound of the average SER as (27).

Appendix E
Proof of Theorem 2

Capitalizing on the techniques proposed in recent works [45], [46], the ergodic capacity of the system can be upper bounded by

$$C_u = \frac{1}{2}\mathrm{E}\left[\log_2\left(1+\frac{\widetilde{\gamma}_1}{1+\gamma_3}\right)\right] + \frac{1}{2}\mathrm{E}\left[\log_2\left(1+\widetilde{\gamma}_2\right)\right] - \frac{1}{2}\log_2\left(1+e^{\mathrm{E}\left[\ln\left(\frac{\widetilde{\gamma}_1}{1+\gamma_3}\right)\right]}+e^{\mathrm{E}\left[\ln\widetilde{\gamma}_2\right]}\right). \quad (65)$$

Now, we start with the first summand in (65), which can be expanded as [47], [48]

$$\mathrm{E}\left[\log_2\left(1+\frac{\widetilde{\gamma}_1}{1+\gamma_3}\right)\right] = \frac{1}{\ln 2}\int_0^{\infty}\frac{1-F_{\gamma_{13}}(x)}{1+x}dx. \quad (66)$$

Substituting (21) into (66), we have

$$\mathrm{E}\left[\log_2\left(1+\frac{\widetilde{\gamma}_1}{1+\gamma_3}\right)\right] = \frac{1}{\ln 2}\sum_{n=0}^{N_{\mathrm{S}}-1}\beta_n\sum_{k=0}^{N_{\mathrm{S}}-n-1}\frac{1}{k!}\left(\frac{1}{\overline{\gamma}_1}\right)^k \times \sum_{i=1}^{\eta(\mathbf{A}_1)}\sum_{j=1}^{\phi_i(\mathbf{A}_1)}\chi_{i,j}(\mathbf{A}_1)\sum_{l=0}^{k}C_l^k\mu_{\langle i\rangle}^l\frac{(l+j-1)!}{(j-1)!} \times \underbrace{\int_0^{\infty}\frac{x^k}{1+x}e^{-\frac{x}{\overline{\gamma}_1}}\left(1+\frac{\mu_{\langle i\rangle}x}{\overline{\gamma}_1}\right)^{-(l+j)}dx}_{I_3}. \quad (67)$$

In order to compute I_3, we first exploit the equality [49, Eq. (8.3.2.21)] as

$$(1+\alpha x)^{-\beta} = \frac{1}{\Gamma(\beta)}G_{1,1}^{1,1}\left[\alpha x\Big|_0^{1-\beta}\right], \quad (68)$$

where $G_{1,1}^{1,1}[\cdot]$ is the Meijer's G function [49, Eq. (8.2.1.1)]. To this end, with the aid of [50, Eq. (2.6.2)], the I_3 can be derived as

$$I_3 = \int_0^{\infty}\frac{x^k e^{-\frac{x}{\overline{\gamma}_1}}}{\Gamma(l+j)}G_{1,1}^{1,1}\left[\frac{\mu_{\langle i\rangle}x}{\overline{\gamma}_1}\,\middle|\,\begin{matrix}1-l-j\\0\end{matrix}\right]G_{1,1}^{1,1}\left[x\Big|_0^0\right]dx = \frac{\overline{\gamma}_1^{k+1}}{\Gamma(l+j)}G_{1,[1:1],0,[1:1]}^{1,1,1,1,1}\left[\mu_{\langle i\rangle},\overline{\gamma}_1\,\middle|\,\begin{matrix}k+1;1-l-j;0\\ --;0;0\end{matrix}\right], \quad (69)$$

where $G_{1,[1:1],0,[1:1]}^{1,1,1,1,1}[\cdot]$ is the generalized Meijer's G function of two variables [51].

Further, to evaluate the second summand, we start by expressing the function $\ln(1+x)$ in terms of Meijer's G function according to [49, Eq. (8.4.6.5)]

$$\ln(1+x) = G_{2,2}^{1,2}\left[x\Big|_{1,0}^{1,1}\right]. \quad (70)$$

$$\begin{aligned}\overline{P}_s^{\mathrm{low}} = & \frac{a}{2}\sqrt{\frac{b}{\pi}}\underbrace{\int_0^\infty \frac{e^{-bx}}{\sqrt{x}}dx}_{I_1} - \frac{a}{2}\sqrt{\frac{b}{\pi}}\sum_{n=0}^{N_{\mathrm{S}}-1}\sum_{k=0}^{N_{\mathrm{S}}-k-1}\frac{\beta_n}{k!}\left(\frac{1}{\overline{\gamma}_1}\right)^k\sum_{l=0}^{k}C_l^k\frac{(l+j-1)!}{(j-1)!} \\ & \times\sum_{m=0}^{M-1}C_m^{M-1}\frac{(-1)^m M\Phi}{(N_{\mathrm{D}}-1)!}\sum_{v=0}^{\varphi}C_v^{\varphi}\frac{\rho_2^v(1-\rho_2)^{\varphi-v}}{(1+m)^{N_{\mathrm{D}}+v}\zeta^{\varphi}}\sum_{q=0}^{N_{\mathrm{D}}+v-1}\frac{\Gamma\left(N_{\mathrm{D}}+\varphi\right)}{\Gamma\left(q+1\right)}\left(\frac{1+m}{\zeta\overline{\gamma}_2}\right)^q \\ & \times\sum_{i=1}^{\eta(\mathbf{A}_1)}\sum_{j=1}^{\phi_i(\mathbf{A}_1)}\frac{\chi_{i,j}\left(\mathbf{A}_1\right)}{\mu_{\langle i\rangle}^{j}}\underbrace{\int_0^\infty x^{q+k-\frac{1}{2}}\left(\frac{1}{\mu_{\langle i\rangle}}+\frac{x}{\overline{\gamma}_1}\right)^{-(l+j)}e^{-\left(b+\frac{1}{\overline{\gamma}_1}+\frac{1+m}{\zeta\overline{\gamma}_2}\right)x}dx}_{I_2}\end{aligned} \tag{63}$$

$$I_2 = \mu_{\langle i\rangle}^{l+j}\left(\frac{\overline{\gamma}_1}{\mu_{\langle i\rangle}}\right)^{k+q+\frac{1}{2}}\Gamma\left(k+q+\frac{1}{2}\right)\Psi\left(k+q+\frac{1}{2},k+q+\frac{3}{2}-l-j,\frac{\overline{\gamma}_1}{\mu_{\langle i\rangle}}\left(b+\frac{1}{\overline{\gamma}_1}+\frac{1+m}{\overline{\gamma}_2\zeta}\right)\right) \tag{64}$$

Then, combining (11) and (70) and with the help of [36, Eq. (7.813.1)], the second summand in (65) can be computed as

$$\begin{aligned}\mathrm{E}\left[\log_2\left(1+\widetilde{\gamma}_2\right)\right] = & \sum_{m=0}^{M-1}\frac{C_m^{M-1}(-1)^m M\Phi}{(N_{\mathrm{D}}-1)!}\sum_{k=0}^{\varphi}\frac{C_k^{\varphi}\Gamma\left(N_{\mathrm{D}}+\varphi\right)}{\Gamma\left(N_{\mathrm{D}}+k\right)} \\ & \times\frac{\rho_2^k(1-\rho_2)^{\varphi-k}}{(1+m)^{N_{\mathrm{D}}+k}\zeta^{\varphi}}G_{3,2}^{1,3}\left[\frac{\zeta\overline{\gamma}_2}{1+m}\middle|\begin{matrix}1-N_{\mathrm{D}}-k,1,1\\1,0\end{matrix}\right].\end{aligned} \tag{71}$$

Now, the remaining task is to compute the third term in (65). Due to the independence of $\widetilde{\gamma}_1$ and γ_3, we have

$$\mathrm{E}\left[\ln\left(\frac{\widetilde{\gamma}_1}{1+\gamma_3}\right)\right] = \mathrm{E}\left[\ln\widetilde{\gamma}_1\right] - \mathrm{E}\left[\ln\left(1+\gamma_3\right)\right]. \tag{72}$$

With the help of the integration relationship [36, Eq. (4.352.1)], we get

$$\mathrm{E}\left[\ln\widetilde{\gamma}_1\right] = \sum_{n=0}^{N_{\mathrm{s}}-1}\beta_n\left[\psi\left(N_{\mathrm{s}}-n\right)+\ln\overline{\gamma}_1\right], \tag{73}$$

where $\psi\left(\cdot\right)$ is the Euler psi function [36, Eq. (8.360)]. In addition, following the similar steps as in the derivation of the second summand in (65), we obtain

$$\mathrm{E}\left[\ln\left(1+\gamma_3\right)\right] = \sum_{i=1}^{\eta(\mathbf{A}_1)}\sum_{j=1}^{\phi_i(\mathbf{A}_1)}\frac{\chi_{i,j}\left(\mathbf{A}_1\right)}{(j-1)!}G_{3,2}^{1,3}\left[\mu_{\langle i\rangle}\middle|_{1,0}^{1-j,1,1}\right]. \tag{74}$$

In addition, due to the fact that the PDFs of $\widetilde{\gamma}_1$ and $\widetilde{\gamma}_2$ have the same form, we get

$$\begin{aligned}\mathrm{E}\left[\ln\widetilde{\gamma}_2\right] = & M\sum_{m=0}^{M-1}\frac{C_m^{M-1}(-1)^m\Phi}{(N_{\mathrm{D}}-1)!}\sum_{k=0}^{\varphi}\frac{C_k^{\varphi}\Gamma\left(N_{\mathrm{D}}+\varphi\right)}{(1+m)^{N_{\mathrm{D}}+k}\zeta^{\varphi}} \\ & \times\rho_2^k(1-\rho_2)^{\varphi-k}\left[\psi\left(N_{\mathrm{D}}+k\right)-\ln\left(\frac{1+m}{\zeta\overline{\gamma}_2}\right)\right].\end{aligned} \tag{75}$$

To this end, pulling everything together, we obtain the upper bound of the ergodic capacity of the system.

Appendix F
Proof of Theorem 2

Substituting (7) into (30) and applying the Jensen's inequality, we obtain the following ergodic capacity lower bound after some simple mathematical manipulations.

$$\begin{aligned}C_l = & \frac{1}{2}\mathrm{E}\left[\log_2\left(1+\frac{\widetilde{\gamma}_1}{1+\gamma_3}\right)\right]+\frac{1}{2}\mathrm{E}\left[\log_2\left(1+\widetilde{\gamma}_2\right)\right] \\ & -\frac{1}{2}\log_2\left(1+\mathrm{E}\left[\frac{\widetilde{\gamma}_1}{1+\gamma_3}\right]+\mathrm{E}\left[\widetilde{\gamma}_2\right]\right).\end{aligned} \tag{76}$$

Since the first two terms in (76) have been obtained in the previous section, the remaining task is to tackle the third term. Due to the independence of $\widetilde{\gamma}_1$ and γ_3, we have

$$\mathrm{E}\left[\frac{\widetilde{\gamma}_1}{1+\gamma_3}\right] = \mathrm{E}\left[\widetilde{\gamma}_1\right] - \mathrm{E}\left[1+\gamma_3\right], \tag{77}$$

where $\mathrm{E}\left[\widetilde{\gamma}_1\right]$ is given by

$$\mathrm{E}\left[\widetilde{\gamma}_1\right] = \overline{\gamma}_1\sum_{n=0}^{N_{\mathrm{S}}-1}\beta_n\left(N_{\mathrm{S}}-n\right)!, \tag{78}$$

where we have used [36, Eq. (3.351.3)] to solving the corresponding integral. Then, substituting (13) into the second term in (77) and exploiting the equation [36, Eq. (9.211.4)], we have

$$\mathrm{E}\left[1+\gamma_3\right] = \sum_{i=1}^{\eta(\mathbf{A}_1)}\sum_{j=1}^{\phi_i(\mathbf{A}_1)}\chi_{i,j}\left(\mathbf{A}_1\right)\mu_{\langle i\rangle}^{-j}\Psi\left(j,j+2,\mu_{\langle i\rangle}^{-1}\right). \tag{79}$$

Similarly, with the help of [36, Eq. (3.351.3)], $\mathrm{E}\left[\widetilde{\gamma}_2\right]$ can be derived as

$$\begin{aligned}\mathrm{E}\left[\widetilde{\gamma}_2\right] = & M\overline{\gamma}_2\sum_{m=0}^{M-1}\frac{C_m^{M-1}(-1)^m\Phi}{(N_{\mathrm{D}}-1)!}\sum_{k=0}^{\varphi}C_k^{\varphi}\Gamma\left(N_{\mathrm{D}}+\varphi\right) \\ & \times\rho_2^k\frac{(1-\rho_2)^{\varphi-k}\left(N_{\mathrm{D}}+k\right)}{(1+m)^{N_{\mathrm{D}}+k+1}\zeta^{\varphi-1}}.\end{aligned} \tag{80}$$

Finally, pulling everything together, the desired result for the lower bound of the ergodic capacity of the system can be obtained.

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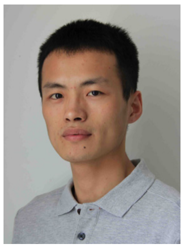

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