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RESEARCH ARTICLE

User selection scheme with limited feedback processing and outdated CSI in multiuser relay networks

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ABSTRACT

A new user selection strategy is investigated and analyzed in a multiuser relaying environment in the presence of co-channel interference. The proposed selection scheme aims at avoiding unnecessary feedback load processing, in cases where a target threshold, in the received instantaneous signal-to-noise ratio, is exceeded. Assuming that perfect channel state information is available, closed-form lower bound expressions are derived for the cumulative distribution function of the output signal to interference plus noise ratio. Moreover, the impact of outdated channel state information on the system's performance is also investigated. In addition, under the assumption of high signal-to-noise ratio conditions, simplified approximated expressions are also provided for the cumulative distribution functions of the output signal to interference plus noise ratio, which are employed to study the outage probability and bit error probability performance of the system. It is shown that with the proposed approach, a significant reduction in feedback load processing is achieved, with only a slight loss in performance. Copyright © 2016 John Wiley & Sons, Ltd.

KEYWORDS
co-channel interference; limited feedback processing; multiuser relay networks; outdated channel state information; threshold-based user selection

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1. INTRODUCTION

Cooperative relaying has been adopted as a promising approach for improving spatial diversity in wireless communications and extending wireless network coverage with low energy budget. Depending upon the requirements in terms of performance and complexity, several relaying protocols have been proposed and studied, including the well-known amplify-and-forward (AF) and decode-and-forward protocols. By applying cooperative relaying to multiuser communication scenarios, a new network architecture has been introduced known as multiuser relay network (MRN) architecture. Such networks have attracted special attention lately both in academia, for example, [1–6], as well as in industrial standards, including IEEE 802.16j mobile multihop relaying [7] and IEEE 802.11s [8]. However, in most cases, it is assumed that these systems operate only in the presence of additive white Gaussian noise (AWGN) effect, despite the fact that in practical situations, because of frequency reuse, the performance of MRNs can be significantly affected by co-channel interference (CCI).

1.1. Related work

The impact of CCI on cooperative relaying systems has been extensively studied for single user scenarios, for example, [9–14]. In [10], the performance of a two hop AF system, where CCI and perfect channel state information (CSI) are available at the relay, was studied. Nevertheless, most of the previous works assume that perfect CSI is available to the system for relay selection. Because of channel estimation errors and feedback delays, such an ideal assumption cannot be established in practice and has only theoretical importance. To overcome this limitation, research efforts have been recently devoted to investigate the impact of outdated CSI on the system's performance for single user scenarios, for example, [15–19]. In [15], the performance of selection cooperation in a cooperative scenario and in the presence of imperfect channel estima-

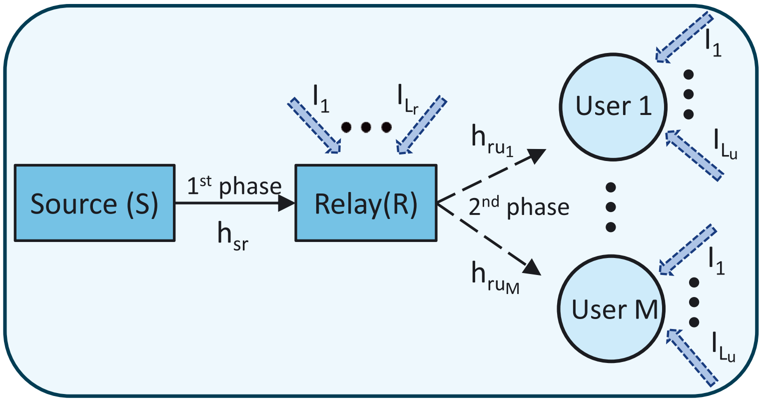

Figure 1. The mode of operation of the proposed threshold-based user selection scheme.

tion was investigated. Moreover, the combined effects of CCI and outdated CSI have been also investigated on multiuser communication scenarios [20–24]. In [20], assuming a MRN in the presence of interferers, where the user selection is based on outdated CSI, tight bounds have been derived for the outage probability (OP) and the symbol error probability. In [21], among several communication scenarios that have been studied, the impact of CSI feedback delay has been investigated for the case where only the relay is subjected to interfering effects. In [23], in a similar communication scenario, several performance metrics have been analytically studied, including the OP, symbol error probability, and the capacity. A common observation in all these works is that the best user selection (BUS) algorithm is adopted; that is, the system selects the user with the best relay-to-user link quality. However, this approach requires increased processing and feedback load overhead, since full CSI feedback is necessary for all users and in each packet transmission, resulting thus to an increase on the uplink feedback load and thus a reduction in the effective throughput of the system [25,26].

1.2. Contribution

Motivated by these observations, in this paper, the new selection scheme proposed in [27] is adopted for user selection in MRN. The new scheme reduces feedback load processing, while achieving almost similar performance to the BUS algorithm. In particular, in the new scheme, it is examined whether the instantaneous signal-to-noise ratio (SNR) of the first active user exceeds a predefined threshold. If this is the case, that user is selected, and thus, no need for examining other users (and further processing) is required. Otherwise, the user having the best channel quality (the highest SNR) among all examined ones is selected by employing full feedback processing. Consequently, upon the selection of an appropriate switching threshold, the proposed approach will result to a significant reduction in the overhead load. In this context, for the system under consideration and assuming perfect channel estimates, we first derive closed-form lower bounds for the cumulative distribution function (CDF) of the output signal to interference plus noise ratio (SINR), which are then used to obtain the OP. Moreover, the outdated CSI scenario is also studied, and the corresponding analytical expression for the OP is provided. In order to gain further insight, we investigate the two previous scenarios in the high SNR regime and provide simplified approximate expressions for the OP and based on them, the average bit error probability (ABEP) is also studied. Summarizing, an analytical framework is proposed in this work for evaluating the impact of interference and outdated CSI to the system's performance, in a novel user selection scheme.

The remainder of this paper is organized as follows. A general description and analysis of the new channel selection strategy are presented in Section 2, complemented with the adopted CSI model. In this context, the CDF of the output SINR and important performance metrics of the proposed approach are studied, considering perfect CSI feedback (in Section 3) as well as outdated CSI feedback (in Section 4). Some numerical and simulation results are presented and discussed in Section 5, while the concluding remarks are given in Section 6.

2. SYSTEM MODEL

We consider a two-phase multiuser cooperative communication network, where the source (S) communicates with M users-destinations U_js with the help of a relay node (R), as shown in Figure 1. The relay selects the user to be served using a threshold-based approach that will be described later. We make the following assumptions:

- No direct link between the source and the mobile users exists, because of severe shadowing.
- The relay node and the users are equipped with single antennas.
- The relay node operates in an AF half-duplex mode, based on the variable gain approach.
- The relay node and each user are subject to AWGN and interference coming from L_r and L_u sources, respectively.

- All links (desired and interfering) are subject to Rayleigh fading, thus modeling a typical macrocellular mobile radio environment [28].

In the first phase, the source transmits a signal s to the relay. The received signal at the relay can be expressed as

$$y_{\rm sr} = h_{\rm sr}\sqrt{P_{\rm s}}s + \sum_{i=1}^{L_{\rm r}} h_{{\rm r}_i}\sqrt{P_i}s_i + w_{\rm sr} \quad (1)$$

where $h_{\rm sr}$ represents the S-R complex Gaussian channel, $P_{\rm s}$ is the average transmitted power, and $w_{\rm sr}$ denotes the AWGN at R, with variance $\sigma_{\rm r}^2$. Moreover, in (1), $h_{{\rm r}_i}$ represents the complex Gaussian channel between the ith interferer and the relay, while P_i is the power of the interfering symbol s_i. In the second phase, the relay transmits a modified version of the received signal to the scheduled user. The signal received by the jth user, $j = 1, \ldots, M$, is given by

$$y_{{\rm ru}_j} = h_{{\rm ru}_j} G y_{\rm sr} + \sum_{i=1}^{L_{\rm u}} h_{{\rm r}_{i,j}}\sqrt{P_{i,j}}s_{i,j} + w_{{\rm ru}_j} \quad (2)$$

where $h_{{\rm ru}_j}$ represents the $R - {\rm U}_j$ complex Gaussian channel gain, $h_{{\rm r}_{i,j}}$ represents the complex Gaussian channel gain between the ith interferer and user j, $P_{i,j}$ is the power of the interfering symbol $s_{i,j}$, and $w_{{\rm ru}_j}$ denotes the AWGN at user j, with variance $\sigma_{\rm u}^2$ for all users. In the AF scheme, which has been also adopted in this paper, the relay nodes cannot differentiate between source and interference signals [29,30]. The amplification process is performed in the analog domain and thus consists of a simple normalization of the total received power without further processing. Thus, the amplifying gain in (2) is given by [10,31]

$$G = \sqrt{\frac{P_{\rm r}}{|h_{\rm sr}|^2 P_{\rm s} + \sum_{i=1}^{L_{\rm r}} |h_{{\rm r}_i}|^2 P_i + \sigma_{\rm r}^2}} \quad (3)$$

where $P_{\rm r}$ denotes the power of the signal transmitted by the relay.

It has been shown that the instantaneous end-to-end SINR at user j is given by [11,21]

$$\gamma_{{\rm sru}_j} = \frac{\gamma_{\rm sr}^{\rm ef}\gamma_{{\rm ru}_j}^{\rm ef}}{\gamma_{\rm sr}^{\rm ef} + \gamma_{{\rm ru}_j}^{\rm ef} + 1} \quad (4)$$

where $\gamma_{\rm sr}^{\rm ef}, \gamma_{{\rm ru}_j}^{\rm ef}$ are the effective SINRs at the relay and jth user, respectively, defined as

$$\gamma_{\rm sr}^{\rm ef} = \frac{P_{\rm s}|h_{\rm sr}|^2/\sigma_{\rm r}^2}{\sum_{i=1}^{L_{\rm r}} P_i|h_{{\rm r}_i}|^2/\sigma_{\rm r}^2 + 1} \text{ and } \\ \gamma_{{\rm ru}_j}^{\rm ef} = \frac{P_{\rm r}|h_{{\rm ru}_j}|^2/\sigma_{\rm u}^2}{\sum_{i=1}^{L_{\rm u}} P_{i,j}|h_{{\rm r}_{i,j}}|^2/\sigma_{\rm u}^2 + 1} \quad (5)$$

2.1. Adopted user selection scheme

In this paper, a new user selection scheme is employed that aims to reduce complexity and feedback load processing [27]. In this scheme, the relay monitors the available channels continuously and selects a user based only on the SNR threshold of the R-U$_j$ link. At the guard period of each packet interval, the relay listens to the requests coming from the M active users, in a similar manner as in [25]. The estimated instantaneous SNR of the firstly probed user is compared with a predefined threshold $\gamma_{\rm th}$, and if it exceeds it, then this user is selected and no further processing is required. Otherwise, the relay identifies the SNR of all active users in the guard period, selects the one with the best relay-user link, similar to BUS, and then feeds back the index to the source. Mathematically speaking, let us define the instantaneous SNR between the relay and the first active user as $\gamma_{{\rm ru}_j} = P_{\rm r}|h_{{\rm ru}_j}|^2/\sigma_{\rm u}^2$. Based on the previous discussion, it is obvious that $\gamma_{{\rm ru}_{\rm sel}} = \gamma_{{\rm ru}_j}$, if $\gamma_{{\rm ru}_j} \geq \gamma_{\rm th}$, otherwise if $\gamma_{{\rm ru}_j} < \gamma_{\rm th}$, then $\gamma_{{\rm ru}_{\rm sel}} = \max\{\gamma_{{\rm ru}_1}, \gamma_{{\rm ru}_2}, \ldots, \gamma_{{\rm ru}_M}\}$, where $u_{\rm sel}$ is the finally selected user. Therefore, the CDF $F_{\gamma_{{\rm ru}_{\rm sel}}}(x)$ of the random variable $\gamma_{{\rm ru}_{\rm sel}}$ is given by

$$F_{\gamma_{{\rm ru}_{\rm sel}}}(x) = \Pr\left[\gamma_{{\rm ru}_{\rm sel}} \leq x\right] \\ = \sum_{j=1}^{M} \Pr\left[\gamma_{{\rm ru}_{\rm sel}} = \gamma_{{\rm ru}_j},\ \gamma_{{\rm ru}_j} \leq x\right] \quad (6)$$

where $\Pr\{\cdot\}$ refers to the probability of the quantity between the brackets. For independent and identically distributed fading, the CDF of $\gamma_{{\rm ru}_{\rm sel}}$ is given by [27]

$$F_{\gamma_{{\rm ru}_{\rm sel}}}(x) = \begin{cases} F_{\gamma_{{\rm ru}_j}}(x) - F_{\gamma_{{\rm ru}_j}}(\gamma_{\rm th}) \\ +F_{\gamma_{{\rm ru}_j}}(\gamma_{\rm th})F_{\gamma_{{\rm ru}_j}}(x)^{M-1}, x \geq \gamma_{\rm th} \\ F_{\gamma_{{\rm ru}_j}}(x)^M, x < \gamma_{\rm th} \end{cases} \quad (7)$$

The corresponding expression for the probability density function (PDF) is

$$f_{\gamma_{{\rm ru}_{\rm sel}}}(x) = \begin{cases} f_{\gamma_{{\rm ru}_j}}(x) + (M-1)F_{\gamma_{{\rm ru}_j}}(\gamma_{\rm th}) \\ \times f_{\gamma_{{\rm ru}_j}}(x)F_{\gamma_{{\rm ru}_j}}(x)^{M-2}, x \geq \gamma_{\rm th} \\ Mf_{\gamma_{{\rm ru}_j}}(x)F_{\gamma_{{\rm ru}_j}}(x)^{M-1}, x < \gamma_{\rm th} \end{cases} \quad (8)$$

The previous general expressions apply to any fading scenario. As mentioned previously, here, we consider that $|h_X|$, with $X \in \{{\rm sr}, {\rm ru}_j, {\rm r}_i, {\rm r}_{i,j}\}$, follows Rayleigh distribution. Therefore, the PDF and CDF expressions of $\gamma_{{\rm ru}_j}$ and $\gamma_{\rm sr} = P_{\rm s}|h_{\rm sr}|^2/\sigma_{\rm r}^2$ are given by

$$f_{\gamma_X}(x) = \frac{1}{\overline{\gamma}_X}\exp\left(-\frac{x}{\overline{\gamma}_X}\right), \\ F_{\gamma_X}(x) = 1 - \exp\left(-\frac{x}{\overline{\gamma}_X}\right) \quad (9)$$

where $\overline{\gamma}_X = \mathbb{E}\left\langle |h_X|^2\right\rangle P_Y/\sigma_Z^2$, with $\mathbb{E}\langle\cdot\rangle$ denoting expectation and $X \in \{{\rm sr}, {\rm ru}_j\}$, $Y \in \{{\rm s}, {\rm r}\}$ and $Z \in \{{\rm r}, {\rm u}\}$, respectively. After the selection is made, the relay feeds back to the source the index of the desired user. In that case, the end-to-end SINR is also given by (4) with $\gamma_{\mathrm{ru}_j}^{\mathrm{ef}}$ replaced by [21]

$$\gamma_{\mathrm{ru}_j}^{\mathrm{ef}} = \frac{\gamma_{\mathrm{ru_{sel}}}}{\sum_{i=1}^{L_u} \gamma_{I_{i,j}} + 1} \tag{10}$$

where $\gamma_{I_{i,j}} = P_{i,j}|h_{\mathrm{r}_{i,j}}|^2/\sigma_{\mathrm{u}}^2$ and $\gamma_{\mathrm{ru_{sel}}}$ denotes the instantaneous SNR of the second-hop link for the selected user. The behavior of the proposed scheme depends on the selected switching threshold γ_{th} for the instantaneous SNR. More specifically, with the increase of γ_{th}, its performance is improved, approaching that of BUS but with the cost of a higher feedback load processing.

2.2. Channel state information model

Regarding the availability of CSI for the R-U$_j$ links at the relay, two scenarios will be investigated in this paper. In the first scenario, studied in Section 3, perfect CSI knowledge of the R-U$_j$ links at the relay will be also considered. In the more practical scenario, examined in Section 4, the CSI of the R-U$_j$ links is assumed outdated, because of the delay existing between the user selection phase and the data transmission phase. In the latter case, the CSI model employed in [16,32] will be also adopted. More specifically, let $\tilde{h}_{\mathrm{ru}_j}$ denote the channel gain between the relay and user j at the selection instance. At the data transmission instance, the actual channel, h_{ru_j}, is related to $\tilde{h}_{\mathrm{ru}_j}$ via the following expression [23,33]

$$h_{\mathrm{ru}_j} = \sqrt{\rho}\tilde{h}_{\mathrm{ru}_j} + \sqrt{1-\rho}\, w_{\mathrm{ru}} \tag{11}$$

where $\rho = J_0(2\pi f_d T_d)$ is the time correlation coefficient between h_{ru_j} and $\tilde{h}_{\mathrm{ru}_j}$, with f_d being the maximum Doppler frequency, T_d is the time delay due to CSI feedback, and $J_0(\cdot)$ is the zeroth-order Bessel function of the first kind [34, equation (8.402)]. Moreover, in (11), w_{ru} is a complex Gaussian random variable with zero mean and the same variance as $\tilde{h}_{\mathrm{ru}_j}$. Thus, the PDF of the actual received SNR of the *selected* user at the data transmission instance can be expressed as [17]

$$\begin{aligned} f_{\gamma_{\mathrm{ru_{sel}}}}(x) &= \int_0^\infty f_{\gamma_{\mathrm{ru_{sel}}}|\tilde{\gamma}_{\mathrm{ru_{sel}}}}(x|y) f_{\tilde{\gamma}_{\mathrm{ru_{sel}}}}(y)dy \\ &= \int_0^\infty \frac{\exp\left[-\frac{\rho y + x}{(1-\rho)\overline{\gamma}_{\mathrm{ru}}}\right]}{(1-\rho)\overline{\gamma}_{\mathrm{ru}}} I_0\left[\frac{2\sqrt{\rho x y}}{(1-\rho)\overline{\gamma}_{\mathrm{ru}}}\right] f_{\tilde{\gamma}_{\mathrm{ru_{sel}}}}(y)dy \end{aligned} \tag{12}$$

where $I_0(\cdot)$ is the zeroth-order modified Bessel function of the first kind [34, equarion (8.445)], $\tilde{\gamma}_{\mathrm{ru_{sel}}}$ is the received SNR at the selection instance, with PDF given by (8), and $\overline{\gamma}_{\mathrm{ru}} = \overline{\gamma}_{\mathrm{ru}_j}, \forall j \in \{1, 2, \ldots, M\}$.

3. PERFORMANCE OF THE PROPOSED SCHEME WITH PERFECT CHANNEL STATE INFORMATION

In this section, the CDF of the system's output SINR is derived when perfect CSI feedback is available at the relay. Moreover, a high SNR analysis is provided, and expressions for two important performance metrics are also derived.

3.1. Exact approach

Employing the exact expression for the end-to-end SINR γ_{sru_j}, provided in (4), will result to a cumbersome mathematical analysis. A mathematically more convenient approach is to use, instead, a tight upper bound of γ_{sru_j}, as in [11], that is,

$$\gamma_{\mathrm{sr\,u}_j} \leq \gamma_{\mathrm{up}} = \min\left\{\gamma_{\mathrm{sr}}^{\mathrm{ef}}, \gamma_{\mathrm{ru}_j}^{\mathrm{ef}}\right\} \tag{13}$$

The CDF of γ_{up} is then given by

$$\begin{aligned} F_{\gamma_{\mathrm{up}}}(\gamma) = \Pr\{\gamma_{\mathrm{up}} \leq \gamma\} = F_{\gamma_{\mathrm{sr}}^{\mathrm{ef}}}(\gamma) \\ + F_{\gamma_{\mathrm{ru}_j}^{\mathrm{ef}}}(\gamma) - F_{\gamma_{\mathrm{sr}}^{\mathrm{ef}}}(\gamma) F_{\gamma_{\mathrm{ru}_j}^{\mathrm{ef}}}(\gamma) \end{aligned} \tag{14}$$

The CDF of $\gamma_{\mathrm{sr}}^{\mathrm{ef}}$ has been previously reported as [11, equation (17)]

$$F_{\gamma_{\mathrm{sr}}^{\mathrm{ef}}}(\gamma) = 1 - \left(\frac{\overline{\gamma}_{\mathrm{sr}}/\overline{\gamma}_{I_{\mathrm{sr}}}}{\overline{\gamma}_{\mathrm{sr}}/\overline{\gamma}_{I_{\mathrm{sr}}} + \gamma}\right)^{L_{\mathrm{r}}} \exp\left(-\frac{\gamma}{\overline{\gamma}_{\mathrm{sr}}}\right) \tag{15}$$

where $\overline{\gamma}_{I_{\mathrm{sr}}} = \overline{\gamma}_{I_{\mathrm{sr}_i}} = \mathbb{E}\left\langle |h_{\mathrm{r}_i}|^2\right\rangle P_i/\sigma_{\mathrm{r}}^2, \forall i \in \{1, 2, \ldots, L_{\mathrm{r}}\}$. In addition, as shown in Appendix A, the CDF of $\gamma_{\mathrm{ru}_j}^{\mathrm{ef}}$ is expressed as

$$\begin{aligned} F_{\gamma_{\mathrm{ru}_j}^{\mathrm{ef}}}(\gamma) &= \exp\left(\frac{1}{\overline{\gamma}_{I_{\mathrm{ru}}}}\right) \frac{M}{\overline{\gamma}_{\mathrm{ru}}} \sum_{i=0}^{L_u-1} \frac{1}{\overline{\gamma}_{I_{\mathrm{ru}}}^i} \sum_{j=0}^{i} \frac{\gamma^{-j}}{(i-j)!} \\ &\times \sum_{k=0}^{M-1} \binom{M-1}{k} \left[1 - \exp\left(-\mathcal{C}_1(\gamma,k)\gamma_{\mathrm{th}}\right) \sum_{p=0}^{j} \right. \\ &\left. \frac{(\mathcal{C}_1(\gamma,k)\gamma_{\mathrm{th}})^p}{p!}\right] \frac{(-1)^{i+k-j}}{\mathcal{C}_1(\gamma,k)^{j+1}} + \exp\left[\left(1 - \frac{\gamma_{\mathrm{th}}}{\gamma}\right)\frac{1}{\overline{\gamma}_{I_{\mathrm{ru}}}}\right] \\ &\times \exp\left(-\frac{\gamma_{\mathrm{th}}}{\overline{\gamma}_{\mathrm{ru}}}\right) \left[\sum_{i=0}^{L_u-1} \sum_{k=0}^{i} \frac{(-1)^{i-k}}{(i-k)!} \frac{\overline{\gamma}_{\mathrm{ru}}^k}{\overline{\gamma}_{I_{\mathrm{ru}}}^i} \sum_{p=0}^{k} \frac{\gamma_{\mathrm{th}}^p \gamma^{1-p}}{p!\overline{\gamma}_{\mathrm{ru}}^p} \right. \\ &\times \left(\gamma + \frac{\overline{\gamma}_{\mathrm{ru}}}{\overline{\gamma}_{I_{\mathrm{ru}}}}\right)^{p-k-1} + F_{\gamma_{\mathrm{ru}}}(\gamma_{\mathrm{th}})(M-1) \sum_{i=0}^{L_u-1} \sum_{k=0}^{i} \\ &\times \sum_{j=0}^{M-2} \frac{\binom{M-2}{j}}{\overline{\gamma}_{I_{\mathrm{ru}}}} \frac{(-1)^j}{(i-k)!} \exp\left(-\frac{j\gamma_{\mathrm{th}}}{\overline{\gamma}_{\mathrm{ru}}}\right) \\ &\left. \times \sum_{p=0}^{k} \frac{\gamma_{\mathrm{th}}^p}{p!} \frac{\gamma^{1-p}\overline{\gamma}_{\mathrm{ru}}^{k-p}}{\left[(1+j)\gamma + \overline{\gamma}_{\mathrm{ru}}/\overline{\gamma}_{I_{\mathrm{ru}}}\right]^{k-p+1}} \right] \end{aligned} \tag{16}$$

where $\mathcal{C}_1(\gamma,k) = \frac{k+1}{\overline{\gamma}_{\mathrm{ru}}} + \frac{1}{\gamma \overline{\gamma}_{I_{\mathrm{ru}}}}$ with $\overline{\gamma}_{I_{\mathrm{ru}}} = \mathbb{E}\left\langle |h_{\mathrm{r}_{i,j}}|^2\right\rangle P_{i,j}/\sigma_{\mathrm{u}}^2$. By substituting (15) and (16) in (14), we obtain $F_{\gamma_{\mathrm{up}}}(\gamma)$.

3.2. High signal-to-noise ratio approach

In order to clearly understand important system-design parameters, we focus here on the high SNR regime. This approach helps us to quantify the amount of performance variations, which are due to the fading effects as well as the scheme's architecture [35]. At the high SNR regime, the exponential PDF and CDF expressions can be approximated by $f_{\gamma_X}(x) \approx \frac{1}{\overline{\gamma}_X}$ and $F_{\gamma_X}(x) \approx \frac{x}{\overline{\gamma}_X}$, respectively. Thus, the CDF of $\gamma_{\mathrm{sr}}^{\mathrm{ef}}$, appearing in (15), simplifies to

$$F_{\gamma_{\mathrm{sr}}^{\mathrm{ef}}}(\gamma) \approx \frac{1+\overline{\gamma}_{I_{\mathrm{sr}}} L_{\mathrm{r}}}{\overline{\gamma}_{\mathrm{sr}}}\gamma \tag{17}$$

Based on the previous approximated expressions for the PDF and CDF and using the same approach as the one employed for deriving (16), the CDF of $\gamma_{\mathrm{ru}_j}^{\mathrm{ef}}$ is obtained in the following simplified form

$$\begin{aligned} F_{\gamma_{\mathrm{ru}_j}^{\mathrm{ef}}}(\gamma) \approx \exp\left(\frac{1}{\overline{\gamma}_{I_{\mathrm{ru}}}}\right) \Bigg\{ \left(\frac{\overline{\gamma}_{I_{\mathrm{ru}}}\gamma}{\overline{\gamma}_{\mathrm{ru}}}\right)^M M \sum_{i=0}^{L_{\mathrm{u}}-1}\sum_{j=0}^{i} & \\ \frac{\binom{i}{j}(-1)^{i-j}}{i!\overline{\gamma}_{I_{\mathrm{ru}}}^{i-j}} \gamma\left(M+j, \frac{\gamma_{\mathrm{th}}}{\gamma\overline{\gamma}_{I_{\mathrm{ru}}}}\right) + \sum_{i=0}^{L_{\mathrm{u}}-1}\sum_{j=0}^{i}\binom{i}{j} & \\ \times \frac{(-1)^{i-j}}{i!\overline{\gamma}_{I_{\mathrm{ru}}}^{i-j}}\left[\frac{\gamma\overline{\gamma}_{I_{\mathrm{ru}}}}{\overline{\gamma}_{\mathrm{ru}}}\Gamma\left(1+j, \frac{\gamma_{\mathrm{th}}}{\gamma\overline{\gamma}_{I_{\mathrm{ru}}}}\right) + F_{\gamma_{\mathrm{ru}}}(\gamma_{\mathrm{th}}) \right. & \\ \left. \times (M-1)\left(\frac{\overline{\gamma}_{I_{\mathrm{ru}}}\gamma}{\overline{\gamma}_{\mathrm{ru}}}\right)^{M-1}\Gamma\left(M+j-1, \frac{\gamma_{\mathrm{th}}}{\gamma\overline{\gamma}_{I_{\mathrm{ru}}}}\right)\right]\Bigg\} & \end{aligned} \tag{18}$$

where $\gamma(\cdot,\cdot)$ and $\Gamma(\cdot,\cdot)$ denote the lower and upper incomplete gamma functions [34, equations (8.350/1 and (8.350/2)]. It is important to note that assuming $\gamma_{\mathrm{th}} \geq \overline{\gamma}_{\mathrm{ru}}$, the second and the third terms in (18) have negligible effect on the system's performance, which results to a diversity gain equal to M. Moreover, by substituting (17) and (18) in (14), we obtain an approximating expression for $F_{\gamma_{\mathrm{up}}}(\gamma)$ in the high SNR regime. However, in that expression, it is evident that $F_{\gamma_{\mathrm{ru}_j}^{\mathrm{ef}}}(\gamma) \ll F_{\gamma_{\mathrm{sr}}^{\mathrm{ef}}}(\gamma)$, which results to a diversity gain equal to 1. Therefore, although multiuser diversity gain at the relay can be achieved in perfect CSI (with $\rho = 1$), because the data transmission has to go through the S-R link, the system performance is dominated by the quality of the weaker hop.

3.3. Performance evaluation

3.3.1. Outage probability.

Outage probability is defined as the probability that the output SINR falls below a predetermined threshold γ_{T} and using (14) can be evaluated as $P_{\mathrm{out}} = F_{\gamma_{\mathrm{up}}}(\gamma_{\mathrm{T}})$.

3.3.2. Average bit error probability.

As shown in Appendix B, in the high SNR regime, the ABEP of differentially binary phase shift keying (DBPSK) is expressed as

$$\begin{aligned} P_{\mathrm{b}} \approx \frac{1}{2}\Bigg\{\frac{1+\overline{\gamma}_{I_{\mathrm{sr}}}L_{\mathrm{r}}}{\overline{\gamma}_{\mathrm{sr}}} + \left[\frac{\exp\left(1/\overline{\gamma}_{I_{\mathrm{ru}}}\right)M}{\overline{\gamma}_{\mathrm{ru}}^M}\mathcal{S}_1(1)\right. & \\ \left. + \exp\left(\frac{1}{\overline{\gamma}_{\mathrm{ru}}}\right)\mathcal{S}_2(2,M)\right] - \frac{1+\overline{\gamma}_{I_{\mathrm{sr}}}L_{\mathrm{r}}}{\overline{\gamma}_{\mathrm{sr}}}\left[\frac{\exp\left(1/\overline{\gamma}_{I_{\mathrm{ru}}}\right)}{\overline{\gamma}_{\mathrm{ru}}^M}\right. & \\ \left. \times M\mathcal{S}_1(2) + \exp\left(\frac{1}{\overline{\gamma}_{\mathrm{ru}}}\right)\mathcal{S}_2(3,M+1)\right]\Bigg\} & \end{aligned} \tag{19}$$

where $\mathcal{S}_1(\cdot), \mathcal{S}_2(\cdot,\cdot)$ are defined in Appendix B. Assuming BPSK and following a similar approach, the corresponding expression for the ABEP is given by

$$\begin{aligned} P_{\mathrm{b}} \approx \frac{a(1+\overline{\gamma}_{I_{\mathrm{sr}}}L_{\mathrm{r}})}{2b\overline{\gamma}_{\mathrm{sr}}} + \frac{a\sqrt{b}}{2\sqrt{2\pi}}\left[\frac{M}{\overline{\gamma}_{\mathrm{ru}}^M}\exp\left(\frac{1}{\overline{\gamma}_{I_{\mathrm{ru}}}}\right)\mathcal{S}_3(1)\right. & \\ \left. + \exp\left(\frac{1}{\overline{\gamma}_{I_{\mathrm{ru}}}}\right)\mathcal{S}_4(1)\right] - \frac{a\sqrt{b}(1+\overline{\gamma}_{I_{\mathrm{sr}}}L_{\mathrm{r}})}{2\sqrt{2\pi}\overline{\gamma}_{\mathrm{sr}}}\left[\frac{M}{\overline{\gamma}_{\mathrm{ru}}^M}\right. & \\ \left. \times \exp\left(\frac{1}{\overline{\gamma}_{I_{\mathrm{ru}}}}\right)\mathcal{S}_3(3) + \exp\left(\frac{1}{\overline{\gamma}_{I_{\mathrm{ru}}}}\right)\mathcal{S}_4(3)\right] & \end{aligned} \tag{20}$$

where $\mathcal{S}_3(x)$ and $\mathcal{S}_4(x)$ are defined as

$$\begin{aligned} \mathcal{S}_3(x) = \sum_{i=0}^{L_{\mathrm{u}}-1}\sum_{j=0}^{i}\frac{(-1)^{i-j}}{j!(i-j)!}\overline{\gamma}_{I_{\mathrm{ru}}}^{M+j-i}\Gamma(M+j) & \\ \times\left[\Gamma\left(M+\frac{x}{2}\right)\left(\frac{2}{b}\right)^{\frac{x}{2}+M} - \sum_{m=0}^{M+j-1}\frac{2}{m!}\left(\frac{\gamma_{\mathrm{th}}}{\overline{\gamma}_{I_{\mathrm{ru}}}}\right)^m\right. & \\ \left. \times\left(\frac{2\overline{\gamma}_{I_{\mathrm{ru}}}}{b\gamma_{\mathrm{th}}}\right)^{\frac{2m-2M-x}{4}} K_{m-M-\frac{x}{2}}\left(\sqrt{\frac{\gamma_{\mathrm{th}}2b}{\overline{\gamma}_{I_{\mathrm{ru}}}}}\right)\right] & \\ \mathcal{S}_4(x) = \sum_{i=0}^{L_{\mathrm{u}}-1}\sum_{j=0}^{i}\frac{(-1)^{i-j}}{j!(i-j)!\overline{\gamma}_{I_{\mathrm{ru}}}^i}\Bigg\{\frac{\overline{\gamma}_{I_{\mathrm{ru}}}^{j+1}}{\overline{\gamma}_{\mathrm{ru}}}\Gamma(j+1)\sum_{m=0}^{j}\frac{2}{m!} & \\ \times\left(\frac{\gamma_{\mathrm{th}}}{\overline{\gamma}_{I_{\mathrm{ru}}}}\right)^m\left(\frac{b\overline{\gamma}_{I_{\mathrm{ru}}}}{2\gamma_{\mathrm{th}}}\right)^{\frac{m}{2}-\frac{x+2}{4}} K_{m-\frac{x+2}{2}}\left(\sqrt{\frac{\gamma_{\mathrm{th}}2b}{\overline{\gamma}_{I_{\mathrm{ru}}}}}\right) & \\ + F_{\gamma_{\mathrm{ru}}}(\gamma_{\mathrm{th}})(M-1)\left(\frac{\overline{\gamma}_{I_{\mathrm{ru}}}}{\overline{\gamma}_{\mathrm{ru}}}\right)^{M-1}\Gamma(M+j-1)\overline{\gamma}_{I_{\mathrm{ru}}}^j & \\ \times\sum_{m=0}^{M+j-2}\frac{2}{m!}\left(\frac{\gamma_{\mathrm{th}}}{\overline{\gamma}_{I_{\mathrm{ru}}}}\right)^m\left(\frac{b\overline{\gamma}_{I_{\mathrm{ru}}}}{2\gamma_{\mathrm{th}}}\right)^{\frac{2m-2M-x+2}{4}} & \\ \times K_{m-M+\frac{2-x}{2}}\left(\sqrt{\frac{\gamma_{\mathrm{th}}2b}{\overline{\gamma}_{I_{\mathrm{ru}}}}}\right)\Bigg\} & \end{aligned}$$

with $K_\nu(\cdot)$ being the second kind modified Bessel function of νth order [34, equation (8.407/1)] and $a = 1/2, b = 1$. The derivation of (20) is based on the conditional error probability of the BPSK modulation scheme, that is,

$P_e(\gamma) = aQ\left(\sqrt{b\gamma}\right)$ with $Q(\cdot)$ being the area under the tail of the Gaussian PDF [28, equation (4.1)] and the approach presented in Appendix B.

4. PERFORMANCE OF THE PROPOSED SCHEME WITH OUTDATED CHANNEL STATE INFORMATION

In this section, the CDF of the system's output SINR is obtained when outdated CSI is available at R. Moreover, a high SNR analysis is provided, and expressions for two important performance metrics are also derived.

4.1. Exact approach

The CDFs of $\gamma_{\rm up}$ and $\gamma_{\rm sr}^{\rm ef}$ are given in (14) and (15), respectively. Moreover, as proved in Appendix C, for outdated CSI, the CDF of $\gamma_{{\rm ru}_j}^{\rm ef}$ is given by

$$\begin{aligned}F_{\gamma_{{\rm ru}_j}^{\rm ef}}(\gamma) = M\sum_{i=0}^{M-1}\frac{\binom{M-1}{i}(-1)^i}{i+1}\{1\\ -\exp\left[-\frac{(1+i)\gamma}{((-\rho)_i)\overline{\gamma}_{\rm ru}}\right]\left[\frac{((-\rho)_i)\overline{\gamma}_{\rm ru}}{(i)\overline{\gamma}_{I_{\rm ru}}\gamma+((-\rho)_i)\overline{\gamma}_{\rm ru}}\right]^{L_{\rm u}}\\ -\mathcal{F}_1\left(\gamma,\overline{\gamma}_{\rm ru},\gamma_{\rm th},\rho,\overline{\gamma}_{I_{\rm ru}},L_{\rm u},i\right)\}\\ +\mathcal{F}_1\left(\gamma,\overline{\gamma}_{\rm ru},\gamma_{\rm th},\rho,\overline{\gamma}_{I_{\rm ru}},L_{\rm u},0\right)\\ +F_{\gamma_{\rm ru}}(\gamma_{\rm th})\sum_{i=0}^{M-2}\frac{\binom{M-2}{i}(-1)^i(M-1)}{i+1}\\ \times\mathcal{F}_1\left(\gamma,\overline{\gamma}_{\rm ru},\gamma_{\rm th},\rho,\overline{\gamma}_{I_{\rm ru}},L_{\rm u},i\right)\end{aligned} \tag{21}$$

where

$$\begin{aligned}&\mathcal{F}_1\left(\gamma,\overline{\gamma}_{\rm ru},\gamma_{\rm th},\rho,\overline{\gamma}_{I_{\rm ru}},L_{\rm u},i\right)\\ &=\exp\left[-\frac{(i)\gamma_{\rm th}}{\overline{\gamma}_{\rm ru}}\right]-\exp\left[-\frac{(1+i)\gamma}{((-\rho)_i)\overline{\gamma}_{\rm ru}}\right]\\ &\times\mathcal{I}\left[L_{\rm u}-1,\frac{1}{\overline{\gamma}_{I_{\rm ru}}},\frac{1+i}{((-\rho)_i)\overline{\gamma}_{\rm ru}},\frac{\sqrt{2\rho/(-\rho)\overline{\gamma}_{\rm ru}}}{\sqrt{1+(-\rho)_i}},\right.\\ &\left.\frac{\sqrt{2((-\rho)_i)\gamma_{\rm th}}}{(-\rho)\overline{\gamma}_{\rm ru}}\right]-\exp\left[-\frac{(i)\gamma_{\rm th}}{\overline{\gamma}_{\rm ru}}\right]\\ &\times\left[1-\mathcal{I}\left[L_{\rm u}-1,\frac{1}{\overline{\gamma}_{I_{\rm ru}}},0,\frac{\sqrt{2}}{\sqrt{(-\rho)\overline{\gamma}_{\rm ru}}},\frac{\sqrt{2\gamma_{\rm th}\rho}}{(-\rho)\overline{\gamma}_{\rm ru}}\right]\right]\end{aligned}$$

with $\mathcal{I}(\cdot)$ defined in Appendix C and $(x)_y = (1+x)y$.

4.2. High signal-to-noise ratio approach

At the high SNR regime, (21) simplifies to

$$\begin{aligned}F_{\gamma_{\rm ru}^{\rm ef}}(\gamma) \approx M\sum_{i=0}^{M-1}\binom{M-1}{i}\frac{(-1)^i}{i+1}\\ \times\mathcal{F}_2\left(\gamma,\overline{\gamma}_{\rm ru},\gamma_{\rm th},\rho,\overline{\gamma}_{I_{\rm ru}},L_{\rm u},i,1,-1\right)\\ +F_{\gamma_{\rm ru}}(\gamma_{\rm th})\sum_{i=0}^{M-2}\binom{M-2}{i}\\ \times(-1)^i\frac{M-1}{i+1}\mathcal{F}_2\left(\gamma,\overline{\gamma}_{\rm ru},\gamma_{\rm th},\rho,\overline{\gamma}_{I_{\rm ru}},L_{\rm u},i,0,1\right)\\ +\mathcal{F}_2\left(\gamma,\overline{\gamma}_{\rm ru},\gamma_{\rm th},\rho,\overline{\gamma}_{I_{\rm ru}},L_{\rm u},0,0,1\right)\end{aligned} \tag{22}$$

where

$$\begin{aligned}&\mathcal{F}_2\left(\gamma,\overline{\gamma}_{\rm ru},\gamma_{\rm th},\rho,\overline{\gamma}_{I_{\rm ru}},L_{\rm u},z,x,y\right)\\ &=\left[1-\left(\frac{1+(-\rho)_z}{1+(-\rho)_z+\gamma(z)\overline{\gamma}_{I_{\rm ru}}/\overline{\gamma}_{\rm ru}}\right)^{L_{\rm u}}\right]\\ &\times\left[x+y\exp\left(-\frac{(1+(-\rho)_z)\gamma_{\rm th}}{(-\rho)\overline{\gamma}_{\rm ru}}\right)\right]\end{aligned}$$

4.3. Performance evaluation

4.3.1. Outage probability.

The OP can be directly evaluated using (14), (15), and (21) as $P_{\rm out} = F_{\gamma_{\rm up}}(\gamma_T)$.

4.3.2. Average bit error probability.

At the high SNR regime, the ABEP of DBPSK under the assumption of feedback delays is given by

$$\begin{aligned}P_{\rm b}\approx\frac{1+\overline{\gamma}_{I_{\rm sr}}L_{\rm r}}{2\overline{\gamma}_{\rm sr}}+\frac{1}{2}\left\{\sum_{i=0}^{M-1}\mathcal{S}_5\mathcal{C}_2(i)+\exp\left(-\frac{\gamma_{\rm th}}{(-\rho)\overline{\gamma}_{\rm ru}}\right)\right.\\ \times\left[1-\left(\frac{\overline{\gamma}_{\rm ru}}{\overline{\gamma}_{I_{\rm ru}}}\right)^{L_{\rm u}}\exp\left(\frac{\overline{\gamma}_{\rm ru}}{\overline{\gamma}_{I_{\rm ru}}}\right)\Gamma\left(1-L_{\rm u},\frac{\overline{\gamma}_{\rm ru}}{\overline{\gamma}_{I_{\rm ru}}}\right)\right]\\ \left.+\sum_{i=0}^{M-2}\mathcal{S}_6\mathcal{C}_2(i)\right\}-\frac{1+\overline{\gamma}_{I_{\rm sr}}L_{\rm r}}{2\overline{\gamma}_{\rm sr}}\left\{\sum_{i=0}^{M-1}\mathcal{S}_5\mathcal{C}_3(i)\right.\\ +\exp\left(-\frac{\gamma_{\rm th}}{(-\rho)\overline{\gamma}_{\rm ru}}\right)\left[1-\frac{\left(\frac{\overline{\gamma}_{\rm ru}}{\overline{\gamma}_{I_{\rm ru}}}\right)^2}{L_{\rm u}-1}\left[\left(L_{\rm u}-1+\frac{\overline{\gamma}_{\rm ru}}{\overline{\gamma}_{I_{\rm ru}}}\right)\right.\right.\\ \left.\left.\left.\times\exp\left(\frac{\overline{\gamma}_{\rm ru}}{\overline{\gamma}_{I_{\rm ru}}}\right){\rm E}_{L_{\rm u}-1}\left(\frac{\overline{\gamma}_{\rm ru}}{\overline{\gamma}_{I_{\rm ru}}}\right)-1\right]\right]+\sum_{i=0}^{M-2}\mathcal{S}_6\mathcal{C}_3(i)\right\}\end{aligned} \tag{23}$$

where $\mathcal{S}_5, \mathcal{S}_6, \mathcal{C}_2(i)$, and $\mathcal{C}_3(i)$ are defined in Appendix D and ${\rm E}_{\rm n}(\cdot)$ is the exponential integral function [34, equation (8.211/1)]. Assuming BPSK, the following approximated closed-form expression for the ABEP is obtained

$$P_{\mathrm{b}} \approx \frac{a(1+\overline{\gamma}_{I_{\mathrm{sr}}}L_{\mathrm{r}})}{2b\overline{\gamma}_{\mathrm{sr}}} + \frac{a\sqrt{b}}{2\sqrt{2}}\left\{\sum_{i=0}^{M-1}\mathcal{S}_5\mathcal{F}_3\left[\frac{((-\rho)_i)\overline{\gamma}_{\mathrm{ru}}}{(i)\overline{\gamma}_{I_{\mathrm{ru}}}},1,1\right]\right.$$
$$\left. + \exp\left[-\frac{\gamma_{\mathrm{th}}}{(-\rho)\overline{\gamma}_{\mathrm{ru}}}\right]\mathcal{F}_3\left(\frac{\overline{\gamma}_{\mathrm{ru}}}{\overline{\gamma}_{I_{\mathrm{ru}}}},1,1\right)\right\} + \sum_{i=0}^{M-2}\mathcal{S}_6$$
$$\times\mathcal{F}_3\left[\frac{((-\rho)_i)\overline{\gamma}_{\mathrm{ru}}}{(i)\overline{\gamma}_{I_{\mathrm{ru}}}},1,1\right] - \frac{a(1+\overline{\gamma}_{I_{\mathrm{sr}}}L_{\mathrm{r}})\sqrt{b}}{2\sqrt{2}\overline{\gamma}_{\mathrm{sr}}}$$
$$\times\left\{\sum_{i=0}^{M-1}\mathcal{S}_5\mathcal{F}_3\left[\frac{((-\rho)_i)\overline{\gamma}_{\mathrm{ru}}}{(i)\overline{\gamma}_{I_{\mathrm{ru}}}},3,\frac{1}{2}\right]+\exp\left[-\frac{\gamma_{\mathrm{th}}}{(-\rho)\overline{\gamma}_{\mathrm{ru}}}\right]\right.$$
$$\left.\times\mathcal{F}_3\left(\frac{\overline{\gamma}_{\mathrm{ru}}}{\overline{\gamma}_{I_{\mathrm{ru}}}},3,\frac{1}{2}\right)\right\} + \sum_{i=0}^{M-2}\mathcal{S}_6\mathcal{F}_3\left[\frac{((-\rho)_i)\overline{\gamma}_{\mathrm{ru}}}{(i)\overline{\gamma}_{I_{\mathrm{ru}}}},3,\frac{1}{2}\right] \quad (24)$$

where

$$\mathcal{F}_3(x,y,z) = \frac{\sqrt{2}}{b^{y/2}} - zx^{y/2}\Psi\left(\frac{y}{2},\frac{y}{2}+1-L_{\mathrm{u}},\frac{b}{2}x\right)$$

with $\Psi(\cdot)$ denoting the confluent hypergeometric function [34, equation (9.210/2)]. The derivation of (24) is based on the conditional error probability of the BPSK modulation scheme and the approach presented in Appendix D.

5. NUMERICAL RESULTS AND PERFORMANCE EVALUATION

In this section, numerical performance evaluation results complemented by Monte Carlo computer simulations are presented for the proposed user selection scheme. For the OP, (14) and (15) will be employed, using also (16) (for perfect CSI feedback) and (21) (for outdated CSI). For the asymptotic results, the simplified expressions given in (17), (18), and (22) are used. Moreover, the DBPSK ABEP performances have been evaluated using (19) and (23) for perfect and outdated CSI, respectively. Finally, the processing complexity of the proposed scheme will be also evaluated by employing the approach that has been also followed in [25]. More specifically, let N_{out} denote the average number of users that must be examined in each packet transmission referred as average feedback load (AFL). Then, the probing time delay (which is proportional to the processing load) can be written as $T_D = N_{\mathrm{out}}T$, where T denotes the time, that is, needed to examine one user. For example, for the BUS scheme, because the requests from all users are continuously examined, the probing time is given by $T_D = MT$. In the proposed scheme, the probability that exactly one user is examined is $\Pr\left\{\gamma_{\mathrm{ru}_j} \geq \gamma_{\mathrm{th}}\right\} = 1 - F_{\gamma_{\mathrm{ru}_j}}(\gamma_{\mathrm{th}})$. Then, based on the total probability law, the AFL is given by

$$N_{\mathrm{out}} = 1 + (M-1)F_{\gamma_{\mathrm{ru}_j}}(\gamma_{\mathrm{th}}) \quad (25)$$

Figure 2 examines the impact of the correlation coefficient ρ to the OP, for different number of users. To obtain this figure, we have assumed average interference to noise ratio $\overline{\gamma}_{I_{\mathrm{sr}}} = \overline{\gamma}_{I_{\mathrm{ru}}} = 0$ dB, switching threshold $\gamma_{\mathrm{th}} = 15$ dB, outage threshold $\gamma_T = 0$ dB, number of interferers $L_{\mathrm{r}} = L_{\mathrm{u}} = 4$, average SNRs $\overline{\gamma}_{\mathrm{sr}} = 13$ dB, and $\overline{\gamma}_{\mathrm{ru}} = 20$ dB. It is depicted that as ρ increases, that is, feedback delay diminishes, and/or the number of users M increases, the OP improves. Moreover, for comparison purposes, the corresponding performance of BUS (at the second hop) is also plotted. It is shown that the OP of both schemes is quite close, especially for smaller values of M, where the performance of the two schemes coincides. However, as it is shown in the table included at the bottom of the graph, the AFL of the proposed scheme is much lower as compared with that of BUS for all M. Figure 3 examines the impact of the switching threshold to the OP, for different number of

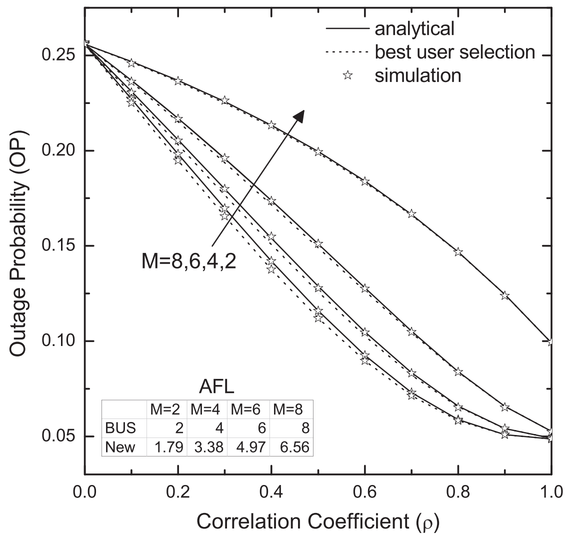

Figure 2. Outage probability (OP) as a function of ρ for different number of users. AFL, average feedback load.

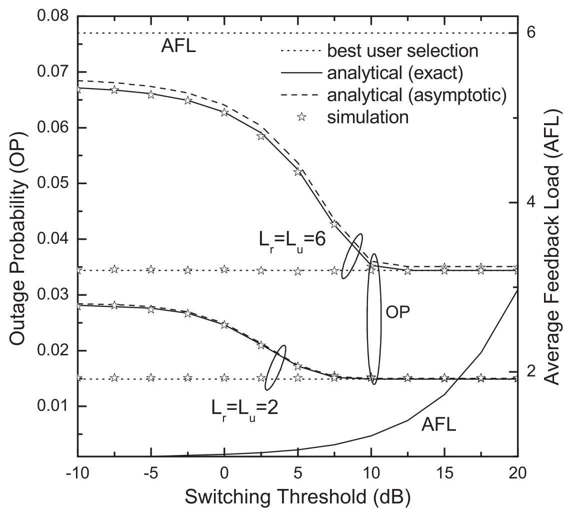

Figure 3. Outage probability (OP) and average feedback load (AFL) as a function of the switching threshold, for different number of interferers.

interferers. To obtain this figure, we have assumed $\overline{\gamma}_{I_{\rm sr}} = \overline{\gamma}_{I_{\rm ru}} = 0$ dB, $\gamma_T = 0$ dB, $M = 6$, $\overline{\gamma}_{\rm sr} = \overline{\gamma}_{\rm ru} = 23$ dB, and perfect CSI, while the performance of BUS is also studied. In Figure 3, it is shown that the performance decreases with the increase of the number of interferers, as expected. It is interesting to note that as $\gamma_{\rm th}$ increases, the performance of the proposed scheme approaches the corresponding one of BUS. However, the AFL of the proposed scheme, which is also shown in this figure, is at least 50% lower than that of BUS. In the same figure, the close agreement between the exact and the asymptotic (high SNR) OP is also clearly depicted. Figure 4 examines the impact of the number of interferers $L_{\rm r} = L_{\rm u}$ to the OP, for different values of $\gamma_{\rm th}$. To obtain this figure we have assumed $\overline{\gamma}_{I_{\rm sr}} = \overline{\gamma}_{I_{\rm ru}} = 0$ dB, $\gamma_T = -20$ dB, $M = 6$, $\overline{\gamma}_{\rm sr} = \overline{\gamma}_{\rm ru} = 0$ dB, $\rho = 0.7$, while the performance of BUS is also included. In all cases, it is shown that the performance of the system decreases with the increase of the number of interferers. It is interesting to note that the decrease of the performance seems to be linear with the increase of the number of interferers, similar to [20]. Moreover, as it is shown in Figure 4, by increasing $\gamma_{\rm th}$, in the proposed scheme, its OP approaches the one of BUS. It is also interesting to note that a substantial AFL reduction is achieved based on the proposed scheme, as compared with the BUS. In particular for $\gamma_{\rm th} = -10$ dB, with a small loss in OP, that is, $< 3\%$, a considerable reduction on the AFL is possible such as $\simeq 30\%$. Figure 5 examines the impact of the feedback delay on the ABEP, for different assumptions on the feedback delay. It is noted that the exact ABEP has been evaluated using simulations. To obtain this figure, we have assumed $\overline{\gamma}_{I_{\rm sr}} = \overline{\gamma}_{I_{\rm ru}} = 5$dB, $\gamma_T = 25$dB, $M = 5$, $L_{\rm r} = L_{\rm u} = 5$. It is interesting to note that the asymptotic curves approximate quite well the exact ones even for moderate values of the average SNR, that is, 20 dB, while the approximation improves for lower values of ρ. Moreover, as it is shown in this figure, the performance of the scheme under consideration decreases with the decrease of the correlation between the channel gains of the selection and data transmission instances. In particular, it seems that an important diversity loss is observed for $\rho \leq 0.6$, while full diversity gain is only available for $\rho = 1$.

Figure 6 examines the impact of the number of users to the OP for different assumptions on the feedback delay. To obtain this figure, we have assumed $\overline{\gamma}_{I_{\rm sr}} = \overline{\gamma}_{I_{\rm ru}} = 7$ dB, $\gamma_T = 0$ dB, $\gamma_{\rm th} = 25$ dB, $L_{\rm r} = L_{\rm u} = 4$. The results shown in Figure 6 confirm that the larger the feedback delay, the

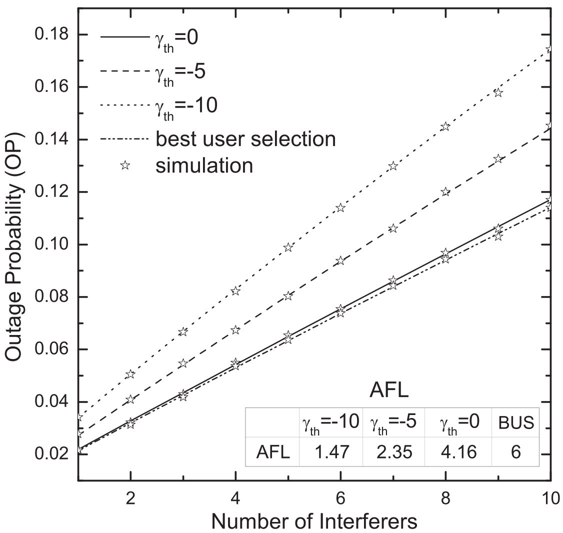

Figure 4. Outage probability (OP) as a function of the number of interferers for different values of $\gamma_{\rm th}$. AFL, average feedback load.

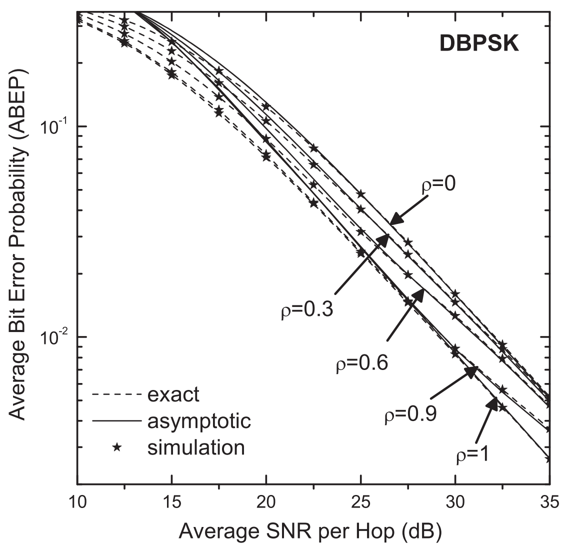

Figure 5. Average bit error probability (ABEP) as a function of the average signal-to-noise ratio (SNR) per hop, for different values of ρ.

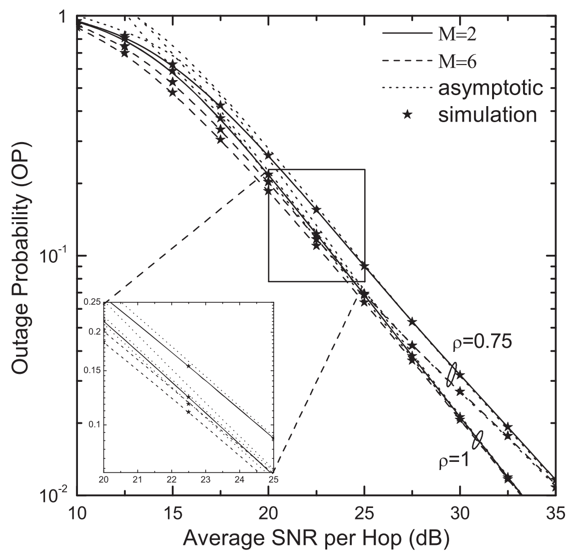

Figure 6. Outage probability (OP) as a function of the average signal-to-noise ratio (SNR) per hop for different number of users.

poorer the OP, while full diversity order can be achieved only when $\rho = 1$. Moreover, as the average SNR per hop increases the impact of the number of users on the system's, OP diminishes. In addition, once more, it is verified that the asymptotic bound is sufficiently tight across the high SNR regime, that is, SNR> 25 dB. Finally, it is important to note that the computer simulations performance results, which are also included in all figures, verify in all cases the validity of the proposed theoretical approach.

6. CONCLUSIONS

In this paper, a threshold-based user selection strategy is proposed and analyzed in a multiuser relay network subjected to CCI effects. The new scheme aims at reducing unnecessary feedback load processing, which characterizes conventional user selection schemes. In this context, assuming that perfect CSI is available, closed-form lower bounds have been derived for the CDF of the output SINR and used to evaluate the OP. Moreover, under the more reasonable assumption of outdated CSI, analytical expressions have been also obtained. In addition, the high SNR regime has been investigated, and simplified approximate expressions for the OP have been extracted for both cases. Based on them, analytical expressions for the ABEP have been obtained for various modulation schemes. In all cases, it was shown that the proposed scheme provides an excellent compromise between performance and system complexity related to feedback overhead processing.

APPENDIX A.

In this Appendix, the derivation of (16) is presented. From (10), the CDF of the output SINR of the proposed scheme is given by

$$\begin{aligned} F_{\gamma_{\text{ru}_j}^{\text{ef}}}(\gamma) &= \Pr\left\{\frac{\gamma_{\text{ru}_{\text{sel}}}}{\gamma_{I_{\text{ru}}}+1} \le \gamma\right\} \\ &= \Pr\left\{\gamma_{\text{ru}_{\text{sel}}} \le \left(\gamma_{I_{\text{ru}}}+1\right)\gamma\right\} \\ &\overset{(i)}{=} \underbrace{\Pr\left\{\gamma_{\text{ru}_{\text{sel}}} \le \left(\gamma_{I_{\text{ru}}}+1\right)\gamma, \gamma_{\text{ru}_{\text{sel}}} \le \gamma_{\text{th}}\right\}}_{P_1} \\ &\quad + \underbrace{\Pr\left\{\gamma_{\text{ru}_{\text{sel}}} \le \left(\gamma_{I_{\text{ru}}}+1\right)\gamma, \gamma_{\text{ru}_{\text{sel}}} > \gamma_{\text{th}}\right\}}_{P_2} \end{aligned} \tag{A-1}$$

where $\gamma_{I_{\text{ru}}} = \sum_{i=1}^{L_{\text{u}}} \gamma_{I_{i,j}}$ is gamma distributed with PDF

$$f_{\gamma_{I_{\text{ru}}}}(x) = \frac{x^{L_{\text{u}}-1}}{\overline{\gamma}_{I_{\text{ru}}}^{L_{\text{u}}}\Gamma(L_{\text{u}})} \exp\left(-\frac{x}{\overline{\gamma}_{I_{\text{ru}}}}\right) \tag{A-2}$$

In (A-1), (i) holds because of the total probability law. Therefore, P_1 and P_2 can be evaluated as follows

$$\begin{aligned} P_1 &= \Pr\left\{\gamma_{I_{\text{ru}}} \ge \frac{\gamma_{\text{ru}_{\text{sel}}}}{\gamma} - 1, \gamma_{\text{ru}_{\text{sel}}} \le \gamma_{\text{th}}\right\} \\ &= \int_0^{\gamma_{\text{th}}} f_{\gamma_{\text{ru}_{\text{sel}}}}(y) \int_{y/\gamma-1}^{\infty} f_{\gamma_{I_{\text{ru}}}}(x)dxdy \end{aligned} \tag{A-3}$$

$$\begin{aligned} P_2 &= \Pr\left\{\gamma_{I_{\text{ru}}} \ge \frac{\gamma_{\text{ru}_{\text{sel}}}}{\gamma} - 1, \gamma_{\text{ru}_{\text{sel}}} > \gamma_{\text{th}}\right\} \\ &= \int_{\gamma_{\text{th}}}^{\infty} f_{\gamma_{\text{ru}_{\text{sel}}}}(y) \int_{y/\gamma-1}^{\infty} f_{\gamma_{I_{\text{ru}}}}(x)dxdy \end{aligned} \tag{A-4}$$

Substituting (8) and (A-2) in (A-4), using [34, equations (8.350/1 and 8.352/1)] and after some mathematical manipulations, (A-1) is expressed as

$$\begin{aligned} F_{\gamma_{\text{ru}_j}^{\text{ef}}}(\gamma) &= \frac{\exp(1/\overline{\gamma}_{I_{\text{ru}}})}{\overline{\gamma}_{\text{ru}}} \Bigg\{ M \sum_{i=0}^{L_{\text{u}}-1} \sum_{j=0}^{i} \frac{\binom{i}{j}(-1)^{i-j}}{\overline{\gamma}_{I_{\text{ru}}}^{i}\, i!\, \gamma^j} \\ &\times \sum_{k=0}^{M-1} \binom{M-1}{k} (-1)^k \int_0^{\gamma_{\text{th}}} y^j \exp\left[-\left(\frac{1}{\gamma\overline{\gamma}_{I_{\text{ru}}}} + \frac{1}{\overline{\gamma}_{\text{ru}}}\right) y\right] dy \\ &+ \sum_{i=0}^{L_{\text{u}}-1} \sum_{k=0}^{i} \frac{\binom{i}{k}(-1)^{i-k}}{\overline{\gamma}_{I_{\text{ru}}}^{i}\, i!\, \gamma^k} \int_{\gamma_{\text{th}}}^{\infty} y^k \exp\left[-\left(\frac{1}{\gamma\overline{\gamma}_{I_{\text{ru}}}} + \frac{1}{\overline{\gamma}_{\text{ru}}}\right) y\right] dy \\ &+ F_{\gamma_{\text{ru}_j}}(\gamma_{\text{th}})(M-1) \sum_{i=0}^{L_{\text{u}}-1} \sum_{k=0}^{i} \frac{\binom{i}{k}(-1)^{i-k}}{\overline{\gamma}_{I_{\text{ru}}}^{i}\, i!\, \gamma^k} \sum_{j=0}^{M-2} \binom{M-2}{j} \\ &(-1)^j \int_{\gamma_{\text{th}}}^{\infty} y^k \exp\left[-\left(\frac{1}{\gamma\overline{\gamma}_{I_{\text{ru}}}} + \frac{1}{\overline{\gamma}_{\text{ru}}}\right) y\right] dy \Bigg\} \end{aligned} \tag{A-5}$$

Applying [34, equations (8.350/1 and 8.350/2)] in (A-5) and after some mathematical simplifications finally yields (16).

APPENDIX B.

In this Appendix, the derivation of (19) is presented. The ABEP can be evaluated as [36]

$$P_{\text{b}} = \int_0^{\infty} -P_e'(\gamma)\, F_{\gamma_{\text{up}}}(\gamma) d\gamma \tag{B-1}$$

where $-P_e'(\gamma)$ denotes the negative derivative of the conditional error probability, for example, for DBPSK modulation, $-P_e'(\gamma) = \alpha\beta\exp(-\beta\gamma)$, where $\alpha = 1/2, \beta = 1$ [36]. Substituting (14), which is based on (17) and (18), in (B-1), integrals of the following forms appear

$$\begin{aligned} \mathcal{I}_1 &= \int_0^{\infty} x^a \exp(-x)\Gamma\left(n, \frac{b}{x}\right) dx \\ &\overset{(i)}{=} \sum_{m=0}^{n-1} \frac{b^m(n-1)!}{m!} \int_0^{\infty} x^{a-m} \exp\left(-x - \frac{b}{x}\right) dx \\ \mathcal{I}_{ii} &= \int_0^{\infty} x^a \exp(-x)\gamma\left(n, \frac{b}{x}\right) dx \overset{(ii)}{=} \Gamma(n)\Gamma(a+1) \\ &\quad - \sum_{m=0}^{n-1} \frac{b^m(n-1)!}{m!} \int_0^{\infty} x^{a-m} \exp\left(-x - \frac{b}{x}\right) dx \end{aligned} \tag{B-2}$$

In (B-2), (*i*) holds because of [34, equation (8.352/2)], while (*ii*) holds because of [34, equations (8.352/1 and 3.381/4)]. Moreover, using [34, equation (3.471/9)] in the solution provided in (B-2) and after some mathematical manipulations yields (19), where

$$\mathcal{S}_1(x) = \sum_{i=0}^{L_u-1}\sum_{j=0}^{i}\frac{(-1)^{i-j}}{j!(i-j)!}\overline{\gamma}_{I_{ru}}^{M+j-i}\Gamma(M+j) \times \left[\Gamma(M+x) - \sum_{m=0}^{M+j-1}\frac{2}{m!}\left(\frac{\gamma_{th}}{\overline{\gamma}_{I_{ru}}}\right)^{\frac{M+m+x}{2}} \times K_{m-M-x}\left(\sqrt{\frac{\gamma_{th}}{\overline{\gamma}_{I_{ru}}}}\right)\right]$$

$$\mathcal{S}_2(x,y) = \sum_{i=0}^{L_u-1}\sum_{j=0}^{i}\frac{(-1)^{i-j}}{j!(i-j)!\overline{\gamma}_{I_{ru}}^{i-j}}\left\{\frac{\overline{\gamma}_{I_{ru}}}{\overline{\gamma}_{ru}}\Gamma(j+1) \times \sum_{m=0}^{j}\frac{2}{m!}\left(\frac{\gamma_{th}}{\overline{\gamma}_{I_{ru}}}\right)^{\frac{m+x}{2}}K_{m-x}\left(2\sqrt{\frac{\gamma_{th}}{\overline{\gamma}_{I_{ru}}}}\right) + F_{\gamma_{ru_j}}(\gamma_{th})(M-1)\left(\frac{\overline{\gamma}_{I_{ru}}}{\overline{\gamma}_{ru}}\right)^{M-1}\Gamma(M+j-1) \times \sum_{m=0}^{M+j-2}\frac{2}{m!}\left(\frac{\gamma_{th}}{\overline{\gamma}_{I_{ru}}}\right)^{\frac{m+y}{2}}K_{m-y}\left(2\sqrt{\frac{\gamma_{th}}{\overline{\gamma}_{I_{ru}}}}\right)\right\}$$

and $K_v(\cdot)$ is the second kind modified Bessel function of vth order [34, equation (8.407/1)].

APPENDIX C.

In this Appendix, the derivation of Equation (21) is presented. The CDF of $\gamma_{ru_j}^{ef}$ can be obtained as

$$F_{\gamma_{ru_j}^{ef}}(\gamma) = \Pr\left\{\frac{\gamma_{ru_{sel}}}{\gamma_{I_{ru}}+1} \le \gamma\right\} = \int_0^{\infty} F_{\gamma_{ru_{sel}}}[\gamma(1+y)]f_{\gamma_{I_{ru}}}(y)dy \quad \text{(C-1)}$$

Moreover, in order to evaluate the CDF of $\gamma_{ru_{sel}}$, its corresponding PDF needs to be evaluated first. Based on (12), the PDF of $\gamma_{ru_{sel}}$ can be written as

$$f_{\gamma_{ru_{sel}}}(x) = \int_0^{\infty} f_{\gamma_{ru_{sel}}|\tilde{\gamma}_{ru_{sel}}}(x|y)f_{\tilde{\gamma}_{ru_{sel}}}(y)dy = \underbrace{\int_0^{\gamma_{th}}\frac{\exp\left(-\frac{\rho y+x}{(-\rho)\overline{\gamma}_{ru}}\right)}{(-\rho)\overline{\gamma}_{ru}}I_0\left(\frac{2\sqrt{\rho xy}}{(-\rho)\overline{\gamma}_{ru}}\right)f_{\tilde{\gamma}_{ru_{sel}}}(y)dy}_{\mathcal{I}_3} + \underbrace{\int_{\gamma_{th}}^{\infty}\frac{\exp\left(-\frac{\rho y+x}{(-\rho)\overline{\gamma}_{ru}}\right)}{(-\rho)\overline{\gamma}_{ru}}I_0\left(\frac{2\sqrt{\rho xy}}{(-\rho)\overline{\gamma}_{ru}}\right)f_{\tilde{\gamma}_{ru_{sel}}}(y)dy}_{\mathcal{I}_4} \quad \text{(C-2)}$$

where $(x)_y = (1+x)y$. For evaluating $\mathcal{I}_3$, (8) is substituted in (C-2), and the binomial identity is used as

$$\mathcal{I}_3 = \frac{M}{\overline{\gamma}_{ru}(-\rho)_{\gamma_{ru}}}\sum_{i=0}^{M-1}\binom{M-1}{i}\exp\left(-\frac{x}{(-\rho)\overline{\gamma}_{ru}}\right) \times \left[\int_0^{\infty}\exp\left(-\frac{1+(-\rho)_i}{(-\rho)\overline{\gamma}_{ru}}y\right)I_0\left(\frac{2\sqrt{\rho xy}}{(-\rho)\overline{\gamma}_{ru}}\right)dy - \int_{\gamma_{th}}^{\infty}\exp\left(-\frac{1+(-\rho)_i}{(-\rho)\overline{\gamma}_{ru}}y\right)I_0\left(\frac{2\sqrt{\rho xy}}{(-\rho)\overline{\gamma}_{ru}}\right)dy\right] \quad \text{(C-3)}$$

The first integral in (C-3) can be directly evaluated using [37, equation (2.15.5/4)], while for the second one, we perform a change of variables and use the first-order Marcum Q-function $Q_1(\cdot)$, [28, equation (4.33)], leading to

$$\mathcal{I}_3 = \frac{M}{(-\rho)\overline{\gamma}_{ru}}\sum_{i=0}^{M-1}\frac{\binom{M-1}{i}(-1)^i}{1+(-\rho)_i}\exp\left(-\frac{x}{(-\rho)\overline{\gamma}_{ru}}\right) \times \left[(1-\rho)\exp\left(\frac{\rho x}{(-\rho)\overline{\gamma}_{ru}((-\rho)_i+1)}\right) - \frac{(-\rho)\overline{\gamma}_{ru}}{\overline{\gamma}_{ru}}\exp\left(\frac{\rho x}{(-\rho)\overline{\gamma}_{ru}+(-\rho)_i(-\rho)\overline{\gamma}_{ru}}\right) \times Q_1\left(\frac{\sqrt{2\rho x}}{(-\rho)\overline{\gamma}_{ru}+(-\rho)_i(-\rho)\overline{\gamma}_{ru}}, \sqrt{2\frac{1+(-\rho)_i}{(-\rho)\overline{\gamma}_{ru}}}\right)\right] \quad \text{(C-4)}$$

Following the same approach, $\mathcal{I}_4$ can be solved as follows

$$\mathcal{I}_4 = \exp\left(-\frac{x}{(-\rho)\overline{\gamma}_{ru}}\right)\frac{1}{\overline{\gamma}_{ru}}\left[\exp\left(\frac{x\rho}{(-\rho)\overline{\gamma}_{ru}}\right) \times Q_1\left(\frac{\sqrt{2\rho x}}{(-\rho)\overline{\gamma}_{ru}}, \sqrt{2\frac{\gamma_{th}}{(-\rho)\overline{\gamma}_{ru}}}\right) + F_{\gamma_{ru_j}}(\gamma_{th})\sum_{i=0}^{M-2}(-1)^i \times \binom{M-2}{i}\frac{M-1}{1+(-\rho)_i}\exp\left(\frac{\rho x}{(-\rho)\overline{\gamma}_{ru}+(-\rho)_i(-\rho)\overline{\gamma}_{ru}}\right) Q_1\left(\frac{\sqrt{2\rho x}}{(-\rho)\overline{\gamma}_{ru}+(-\rho)_i(-\rho)\overline{\gamma}_{ru}}, \sqrt{2\frac{1+(-\rho)_i}{(-\rho)\overline{\gamma}_{ru}}}\right)\right] \quad \text{(C-5)}$$

The CDF of $\gamma_{ru_{sel}}$ can be evaluated as $F_{\gamma_{ru_{sel}}}(y) = \int_0^y f_{\gamma_{ru_{sel}}}(x)dx = \int_0^y \mathcal{I}_3 dx + \int_0^y \mathcal{I}_4 dx$. As far as the first integral is concerned and based on (C-4), integrals of the following form appear

$$\mathcal{I}_5 = \int_0^y \exp\left[-\left(\frac{1}{(-\rho)\overline{\gamma}_{ru}} - \frac{\rho}{(-\rho)\overline{\gamma}_{ru}(1+(-\rho)_i)}\right)x\right]dx$$
$$\mathcal{I}_6 = \int_0^y \exp\left[-\left(\frac{1}{(-\rho)\overline{\gamma}_{ru}} - \frac{\rho}{(-\rho)\overline{\gamma}_{ru}(1+(-\rho)_i)}\right)x\right] \times Q_1\left[\frac{\sqrt{2\rho x}}{(-\rho)\overline{\gamma}_{ru}(1+(-\rho)_i)}, \sqrt{2\frac{1+(-\rho)_i}{(-\rho)\overline{\gamma}_{ru}}}\right]dx \quad \text{(C-6)}$$

$$
\begin{aligned}
F_{\gamma_{\mathrm{ru_{sel}}}}(x) = M \sum_{i=0}^{M-1} \frac{\binom{M-1}{i}(-1)^i}{1+i} \Bigg[1 - \exp\left(-\frac{(i)\gamma_{\mathrm{th}}}{\overline{\gamma}_{\mathrm{ru}}}\right) Q_1\left(\frac{\sqrt{2x}}{(-\rho)\overline{\gamma}_{\mathrm{ru}}}, \sqrt{\frac{2\gamma_{\mathrm{th}}\rho}{(-\rho)\overline{\gamma}_{\mathrm{ru}}}}\right) - \exp\left(-\frac{(1+i)x}{\overline{\gamma}_{\mathrm{ru}}(1+(-\rho)_i)}\right) \\
\times \left[1 - Q_1\left(\frac{\sqrt{2\rho x}}{(-\rho)\overline{\gamma}_{\mathrm{ru}} + (-\rho)_i(-\rho)\overline{\gamma}_{\mathrm{ru}}}, \sqrt{2\frac{1+(-\rho)_i}{(-\rho)\overline{\gamma}_{\mathrm{ru}}}\gamma_{\mathrm{th}}}\right)\right]\Bigg] + \exp\left(-\frac{\gamma_{\mathrm{th}}}{\overline{\gamma}_{\mathrm{ru}}}\right) Q_1\left(\frac{\sqrt{2x}}{(-\rho)\overline{\gamma}_{\mathrm{ru}}}, \sqrt{\frac{2\gamma_{\mathrm{th}}}{(-\rho)\overline{\gamma}_{\mathrm{ru}}}}\right) \\
- \exp\left(-\frac{x}{\overline{\gamma}_{\mathrm{ru}}}\right) Q_1\left(\frac{\sqrt{2\rho x}}{(-\rho)\overline{\gamma}_{\mathrm{ru}}}, \sqrt{\frac{2\gamma_{\mathrm{th}}\rho}{(-\rho)\overline{\gamma}_{\mathrm{ru}}}}\right) + F_{\gamma_{\mathrm{ru}_j}}(\gamma_{\mathrm{th}}) \sum_{i=0}^{M-2} \binom{M-2}{i} (-1)^i \frac{M-1}{i+1} \left[\exp\left(-\frac{(i)\gamma_{\mathrm{th}}}{\overline{\gamma}_{\mathrm{ru}}}\right) \right. \\
\left. \times Q_1\left(\frac{\sqrt{2x}}{(-\rho)\overline{\gamma}_{\mathrm{ru}}}, \sqrt{\frac{2\gamma_{\mathrm{th}}\rho}{(-\rho)\overline{\gamma}_{\mathrm{ru}}}}\right) - \exp\left(-\frac{(1+i)x}{(1+(-\rho)_i)\overline{\gamma}_{\mathrm{ru}}}\right) Q_1\left(\frac{\sqrt{2\rho x}}{(-\rho)\overline{\gamma}_{\mathrm{ru}} + (-\rho)_i(-\rho)\overline{\gamma}_{\mathrm{ru}}}, \sqrt{\frac{2(1+(-\rho)_i)\gamma_{\mathrm{th}}\rho}{(-\rho)\overline{\gamma}_{\mathrm{ru}}}}\right)\right]
\end{aligned}
\tag{C-7}
$$

The solution of $\mathcal{I}_5$ is straightforward. As far as $\mathcal{I}_6$ is concerned, it can be solved in closed form by making a change of variables of the form $\sqrt{x} = y$ and using [38, equations (12 and 14)]. Using the same approach for the second integral also and after some mathematical manipulations yields (C-7).

Finally, substituting (C-7) in (C-1), the following two forms of integrals appear

$$
\begin{aligned}
\mathcal{I}_7 &= \int_0^\infty x^n \exp(-\mu x) dx \overset{(i)}{=} n! \mu^{-n-1} \\
\mathcal{I}_8 &= \int_0^\infty x^a \exp(-bx) Q_1\left(d\sqrt{\gamma(1+x)}, e\right) \\
&\quad \times \exp[-c\gamma(1+x)]\, dx \overset{(ii)}{=} \exp(b) \sum_{i=0}^{a} \binom{a}{i} \frac{(-1)^{a-i}}{\left(d^2\gamma\right)^{i+1}} \\
&\quad \times \Bigg(\underbrace{\int_0^\infty x^i \exp\left[-\frac{(b+c\gamma)}{d^2\gamma}x\right] Q_1\left(\sqrt{x}, e\right) dx}_{\mathcal{I}_{8,a}} \\
&\quad - \underbrace{\int_0^{d^2\gamma} x^i \exp\left[-\frac{(b+c\gamma)}{d^2\gamma}x\right] Q_1\left(\sqrt{x}, e\right) dx}_{\mathcal{I}_{8,b}} \Bigg)
\end{aligned}
\tag{C-8}
$$

In (C-8), (i) is based on [34, equation (3.351/3)] and (ii) is based on the binomial identity, because $a \in \mathbb{N}$, and on a change of variables. The first integral in $\mathcal{I}_8$ of (C-8) can be directly evaluated using [38, equation (9)] as

$$
\begin{aligned}
\mathcal{I}_{8,a} = i!(d^2\gamma)^{2-i} \exp\left[-\frac{e^2(b+c\gamma)}{2(b+c\gamma)+d^2\gamma}\right]\epsilon_k \\
\times \frac{2^k(b+c\gamma)^{k-i-1}}{\left(2(b+c\gamma)+d^2\gamma\right)^{k+1}} L_k\left[-\frac{e^2d^2\gamma/2}{\left(2(b+c\gamma)+d^2\gamma\right)}\right]
\end{aligned}
\tag{C-9}
$$

where $\epsilon_k \equiv 1$, if $k < i$, or $\epsilon_k \equiv 1 + 2(b+c\gamma)/(d^2\gamma)$, if $k = i$, and $L_n(x)$ denotes the Laguerre polynomial [34, equation (8.970/2)]. As far as $\mathcal{I}_{8,b}$ is concerned, integration by parts will be employed. Thus, using [34, equation (2.321/2)] and [39, equation (8)], making a change of variable, and using [39, equation (14)] yields

$$
\begin{aligned}
\mathcal{I}_{8,b} &= \frac{i!}{\mathcal{A}^{i+1}} \Bigg\{ \left[1 - \exp\left(-(b+c\gamma)\right) \sum_{k=0}^{i} \frac{(b+c\gamma)^k}{k!}\right] Q_1\left(d\sqrt{\gamma}, e\right) - \exp\left(-\frac{e^2}{2}\right) \Bigg[\exp\left(\frac{e^2}{2}\right) Q_1\left(d\sqrt{\gamma}, e\right) \\
&\quad -1 - \sum_{k=0}^{i} \frac{e}{k!} \int_0^{d\sqrt{\gamma}} \exp\left[-\left(\mathcal{A}+\frac{1}{2}\right)y^2\right] \left(\mathcal{A}y^2\right)^k I_1(ey) dy \Bigg]\Bigg\} \\
&\overset{(i)}{=} \frac{i!}{\mathcal{A}^{i+1}} \Bigg\{ \left[1 - \exp\left(-(b+c\gamma)\right) \sum_{k=0}^{i} \frac{(b+c\gamma)^k}{k!}\right] Q_1\left(d\sqrt{\gamma}, e\right) - \exp\left(-\frac{e^2}{2}\right) \Bigg[\exp\left(\frac{e^2}{2}\right) Q_1\left(d\sqrt{\gamma}, e\right) \\
&\quad -1 - \sum_{k=0}^{i} \frac{e\mathcal{A}^k}{k!} \left[\frac{\pi e/4}{(\mathcal{A}+1/2)^{k+1}} G_{2,3}^{1,1}\left(\frac{e^2/4}{\mathcal{A}+1/2}\,\middle|\, {}_{-k,\frac{1}{2} 0,-1,\frac{1}{2}}\right)\right. \\
&\quad \left. - \frac{\exp\left(e^2/\left(4\mathcal{A}+1/2\right)\right)}{\left(2(\mathcal{A}+1/2)\right)^{k+1/2}}\right] Q_{2k,1}\left(\frac{e}{\sqrt{2(\mathcal{A}+1/2)}}, d\sqrt{2(\mathcal{A}+1/2)\gamma}\right)\Bigg]\Bigg\}
\end{aligned}
\tag{C-10}
$$

$$\mathcal{I}(a,b,c,d,e,\gamma) = \exp(b+c\gamma)\sum_{i=0}^{a}\frac{b^{a+1}}{(a-i)!}\frac{(-1)^{a-i}}{(b+c\gamma)^{i+1}}\left\{\frac{d^2\gamma}{2(b+c\gamma)+d^2\gamma}\exp\left[-\frac{e^2(b+c\gamma)}{2(b+c\gamma)+d^2\gamma}\right]\right.$$
$$\times\sum_{k=0}^{i}\epsilon_k\left[\frac{2(b+c\gamma)}{2(b+c\gamma)+d^2\gamma}\right]^k L_k\left(-e^2\mathcal{B}\right)-\left[\left[1-\exp\left[-(b+c\gamma)\right]\sum_{k=0}^{i}\frac{(b+c\gamma)^k}{k!}Q_1\left(\sqrt{d^2\gamma},e\right)\right]\right.$$
$$-\left[Q_1\left(d\sqrt{\gamma},e\right)-\exp\left(-\frac{e^2}{2}\right)-e\exp\left(-\frac{e^2}{2}\right)\sum_{k=0}^{i}\frac{1}{k!}\frac{(b+c\gamma)^k\sqrt{d^2\gamma}}{(2(b+c\gamma)+d^2\gamma)^{k+1/2}}\left[2^{k-1}\pi\sqrt{2e^2\mathcal{B}}\right.\right.$$
$$\left.\left.\left.\left.\times\ \mathcal{G}_{2,3}^{1,1}\left(e^2\mathcal{B}\middle|\begin{matrix}-k,1/2\\0,-1,1/2\end{matrix}\right)-\exp\left(e^2\mathcal{B}\right)Q_{2k,1}\left[e\sqrt{2\mathcal{B}},\sqrt{2(b+c\gamma)+d^2\gamma}\right]\right]\right]\right]\right\}$$

where $\mathcal{A}=\frac{(b+c\gamma)}{d^2\gamma}$ and $\mathcal{G}_{p,q}^{m,n}[\cdot|\cdot]$ is the Meijer's G-function [34, equation (9.301)] and $Q_{m,n}(a,b)$ is the Nuttall's Q-function defined in [28, equation (4.104)]. For obtaining (i) in (C-10), the Meijer G-function representations have been employed for $I_v(\cdot)$ and $\exp(\cdot)$, using [40, equation (03.02.26.0006.01)] and [41, equation (11)], respectively, while the final solution is provided based on [41, equation (21)] and using the definition of the Nuttal Q-function [28, equation (4.104)]. After performing several mathematical manipulations and simplifications, (21) is derived where $\mathcal{I}$ is defined at the top of this page and $\mathcal{B}=\frac{d^2\gamma/2}{2(b+c\gamma)+d^2\gamma}$.

It should be noted that all functions appearing in (C-10), except the Nuttal Q, are built-in functions in many mathematical software packages. As far as Nuttal Q-function is concerned, because it is not a tabulated function, in order to be evaluated, it can be expressed in terms of the first-order Marcum Q-function using [39, equation (13)] and the generalized Marcum Q-function based on [28, equation (4.110)].

APPENDIX D.

In this Appendix, the derivation of (23) is presented. Substituting (14), which is based on (17) and (22), in (B-1) integrals of the following forms appear

$$\mathcal{I}_9=\int_0^\infty\frac{\exp(-px)}{(x+z)^t}dx\overset{(i)}{=}p^{t-1}\exp(pz)\Gamma(1-t,pz)$$
$$\mathcal{I}_{10}=\int_0^\infty x^{a-1}\frac{\exp(-px)}{(x+z)^t}dx\overset{(ii)}{=}\Gamma(a)z^{a-t}\Psi(a,a+1-t;pz)$$
$$\overset{(iii)}{=}\frac{\Gamma(a)z^{a-t}}{a-t-1}\left[1-\exp(pz)\left(1-a+t+pz\right)\mathrm{E}_{1-a}(pz)\right] \quad \text{(D-1)}$$

In (D-1), (i) holds because of [42, equation (2.3.4/2)], while (ii) holds because of [42, equation (2.3.6/9)], with $\Psi(\cdot)$ denoting the confluent hypergeometric function [34, equation (9.210/2)]. Moreover, using [40, equations (07.33.03.0015.01 and 06.06.27.0003.01)], $\mathcal{I}_{10}$ further simplifies as shown after the third equality (iii) in (D-1). Based on the previous presented solutions and after some mathematical manipulations, (23) is finally derived. In (23),

$$\mathcal{S}_5=M\binom{M-1}{i}\frac{(-1)^i}{i+1}\left[1-\exp\left(-\frac{((-\rho)_i)\gamma_{\rm th}}{(-\rho)\overline{\gamma}_{\rm ru}}\right)\right]$$
$$\mathcal{S}_6=\left[1-\exp\left(-\frac{\gamma_{\rm th}}{\overline{\gamma}_{\rm ru}}\right)\right]\binom{M-2}{i}\times\frac{(-1)^i(M-1)}{i+1}\exp\left(-\frac{((-\rho)_i)\gamma_{\rm th}}{(-\rho)\overline{\gamma}_{\rm ru}}\right)$$
$$\mathcal{C}_2(i)=1-\left(\frac{((-\rho)_i)\overline{\gamma}_{\rm ru}}{(i)\overline{\gamma}_{I_{\rm ru}}}\right)^{L_{\rm u}}\exp\left(\frac{((-\rho)_i)\overline{\gamma}_{\rm ru}}{(i)\overline{\gamma}_{I_{\rm ru}}}\right)\times\Gamma\left(1-L_{\rm u},\frac{((-\rho)_i)\overline{\gamma}_{\rm ru}}{(i)\overline{\gamma}_{I_{\rm ru}}}\right)$$
$$\mathcal{C}_3(i)=1-\left(\frac{((-\rho)_i)\overline{\gamma}_{\rm ru}}{(i)\overline{\gamma}_{I_{\rm ru}}}\right)^2\frac{1}{L_{\rm u}-1}\left[\left(L_{\rm u}-1+\frac{((-\rho)_i)\overline{\gamma}_{\rm ru}}{(i)\overline{\gamma}_{I_{\rm ru}}}\right)\right.\times\exp\left(\frac{((-\rho)_i)\overline{\gamma}_{\rm ru}}{(i)\overline{\gamma}_{I_{\rm ru}}}\right)\left.\mathrm{E}_{L_{\rm u}\text{-}1}\left(\frac{((-\rho)_i)\overline{\gamma}_{\rm ru}}{(i)\overline{\gamma}_{I_{\rm ru}}}\right)-1\right]$$

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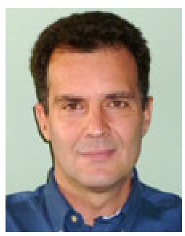

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