A More Realistic System Modeling for Multiuser Two-Hop Cooperative Relay Wireless Networks

Daniel Benevides da Costa, Haiyang Ding, and Jianhua Ge

***Resumo*— Uma discussão acurada baseada no modelo de sistema apresentado em [1] é realizada. Mais especificamente, uma modelagem de sistema mais realística para redes sem fio multiusuário com relay é proposta. A partir dessa nova modelagem, expressões exatas e em forma fechada para as probabilidades de *outage* de protocolos fixos decodifica-e-encaminha (F-DF) e protolocos seletivos DF (S-DF) são obtidas e uma análise dos respectivos ganhos de diversidade é feita. Tanto a análise teórica como as simulações revelam que, sob esta nova modelagem de sistema, a ordem de diversidade obtida com o protocolo F-DF permanece igual a M (M representando o número de usuários), que é a mesma que aquela apresentada em [1], enquanto que a ordem de diversidade do protocolo S-DF reduz de $2M$ para $M+1$.**

***Palavras-Chave*— Comunicações cooperativas, ganho de diversidade, probabilidade de *outage*, diversidade multiusuário.**

***Abstract*— A detailed discussion regarding the system model presented in [1] is provided. More specifically, a more realistic system modeling for multiuser two-hop cooperative relay wireless networks is proposed. Based on this new system modeling, we derive exact closed-form expressions for the outage probabilities of fixed decode-and-forward (F-DF) and selective DF (S-DF) protocols, from which the respective diversity analysis are performed. Both theoretical analysis and simulations show that the achieved diversity order from F-DF protocol under the new system modeling is still M (M denoting the number of users), which is the same with that presented in [1], whereas the diversity order of the S-DF protocol reduces from $2M$ to $M+1$.**

***Keywords*— Cooperative communications, diversity gain, outage probability, multiuser diversity.**

I. Introduction

Cooperative diversity has been recognized as an efficient and low cost technique to combat multipath fading in wireless environments. In this case, the diversity gains are achieved via collaboration between the mobile nodes to form a virtual antenna array and can yield important benefits over direct transmission systems, such as good scalability, increased connectivity, robustness to channel impairments, and energy efficiency [2], [3]. On the other hand, multiuser diversity (MUD) is an important kind of diversity inherent in multiuser systems, which exploits the fact that users undergo independently varying channels and, at any time, there must be a user whose channel gain is near the peak. Then, the system can choose to serve this user at that time. Exploiting multiuser diversity is an important way of improving spectral efficiency in multiuser networks. Actually, it has been proven along the years that by letting only the 'best' user to transmit at a certain time, MUD can be achieved in the form of increased system diversity order or increased total throughput [4].

D. B. da Costa is with the Federal University of Ceara - Campus Sobral, CE, Brazil (email: danielbcosta@ieee.org). This work is supported by the FUNCAP (Grant No. BP1-0031-00090.01.00/10).

H. Ding and J. Ge are with the State Key Laboratory of Integrated Service Networks, Xidian University, Xi'an, China. H. Ding is also with Xi'an Communication Institute, Xi'an, China (e-mails: dinghy2003@hotmail.com, jhge@xidian.edu.cn).

The subject of MUD has already extensively investigated in literature ([5], [6] and references therein). However, to the best of our knowledge, there are few works addressing the combined use of multiuser diversity and cooperative diversity. In [7], the authors studied these two important concepts in a decentralized environment, with the emphasis on the improvement of system throughput. The capacity of the cooperative networks exploiting MUD was discussed in [8] and [9]. In [1], the analysis of MUD in cooperative networks with a single relay was presented, focusing on the diversity performance of the system. Afterwards, the results of [1] were extended to multi-source multi-relay networks in [10].

In this paper, relying on the system framework presented in [1], we propose a more realistic system modeling for multiuser two-hop cooperative relay wireless networks. Based on this new system modeling, we derive exact closed-form expressions for the outage probabilities of fixed decode-and-forward (F-DF) and selective DF (S-DF) protocols, from which the respective diversity analysis are performed. Both theoretical analysis and simulations show that the achieved diversity order from F-DF protocol under the new system modeling is still M (M denoting the number of users), which is the same with that presented in [1], whereas the diversity order of the S-DF protocol reduces from $2M$ to $M+1$.

The remainder of this paper is organized as follows. In Section II, a more realistic system modeling for the system framework presented in [1] is proposed. In Section III, we analyze the achieved outage performance and diversity order of F-DF and S-DF protocols under the system modified framework. Numerical results and discussions are provided in Section IV, in which an outage performance comparison between the F-DF and S-DF protocols of the original (i.e., [1]) and modified system frameworks is performed Finally, concluding remarks are drawn in Section V.

II. A More Realistic System Modeling

The recent work by Zhang *et al.* [1] investigated the topic of "multiuser diversity in multiuser two-hop cooperative relay wireless networks". A fundamental part of this investigation was the modeling of a system framework for multiuser two-hop cooperative relay wireless networks. To facilitate the subsequent discussions, next we shall briefly summarize the scenario considered in [1].

Consider a multiuser diversity (MUD) system, where M users $(S_1, ..., S_M)$ compete to make access to the base station (destination D) with the aid of one relay (R). A time-division multiple-access (TDMA) scheme is used for orthogonal channel access and, at a given time, the best user out of the total M users is selected for transmission. All the channel state information (CSI) can be properly obtained at the base station D for MUD-based scheduling. Similar to [1], we assume that all the noise variances are equal to N_0 and we define $\bar{\gamma} \triangleq 1/N_0$ as the system signal-to-noise ratio (SNR) since this term is proportional to all transmit and receive SNR in the system [11]. In addition, let $\gamma_{S_mD} \triangleq P_{S_m}|h_{S_mD}|^2/N_0$, $\gamma_{S_mR} \triangleq P_{S_m}|h_{S_mR}|^2/N_0$ and $\gamma_{RD} \triangleq P_R|h_{RD}|^2/N_0$ be the received SNR at D from S_m $(m = 1, ..., M)$, at R from S_m, and at D from R, respectively. Herein, P_{S_m} and P_R represent the transmit powers of S_m and R, respectively, and h_{S_mD}, h_{S_mR}, and h_{RD} are the channel coefficients of the links $S_m \to D$, $S_m \to R$ and $R \to D$, respectively. We assume that the channels pertaining to each link undergo independent Rayleigh flat fading. Consequently, $|h_{S_mD}|^2$, $|h_{S_mR}|^2$, and $|h_{RD}|^2$ conform to exponential distribution with mean μ_{S_mD}, μ_{S_mR}, and μ_{RD}, respectively.

It is noteworthy that, differently from [1], the channel coefficient h_{RD} mentioned above does not contain the index m due to the reasons outline below:

(a) If we model all the terminals as single-antenna devices (which is usually the case in cooperative networks but is not clearly stated in [1]), the channel fading pertaining to the single link $R \to D$ has only one degree of freedom and therefore cannot be further modified, differently from the channel fading inherent to the multiple potential links pertaining to the first-hop transmission. Moreover, to ensure a fair multiuser selection process, the link $R \to D$ should exhibit the same (flat) fading characteristic for different potential users during each user-selection process. Otherwise, if the fading amplitude pertaining to the link $R \to D$ varies for different potential users during the user-selection process (a fast fading scenario), the fading amplitude of the link $R \to D$ should have changed to an unknown value at the instant when the selected user transmits and consequently, the MUD is not valid any more.

(b) If h_{RD} were written as h_{RD}^m, as done in [1], it may mean that there are M different links between R and D for the M potential users, implying that the destination should have multiple antennas. However, this assumption may not be true since the authors never claim this assumption in [1] and in their subsequent work [10], which is an extension of [1] for multiple relays.

(c) Even if the destination has multiple antennas, note that assuming h_{RD}^m for the m-th potential user is still not a good strategy. This is due to the fact that since it has been assumed that all the CSI can be properly obtained at D for MUD-based scheduling, the base station could have selected the best link out of the M links between R and D for users to access. By doing so, the system can provide each potential user with the best link quality. Nevertheless, in this case, the analytical approach given in [1] fails whereas the counterpart proposed in this letter is still applicable.

Therefore, although we have proposed a minor modification for the link $R \to D$, this correction is absolutely necessary due to the reasons outlined above and, more importantly, the corresponding diversity order reduces from $2M$ to $M + 1$ for S-DF protocol, which is a significant change for a multiuser cooperative system. It becomes therefore not that optimistic for the achievable outage behavior and diversity order of a single-relay cooperative system serving for M users. Besides, the original analytical method fails and we have to resort to new approaches to analyze the outage behavior of such systems.

III. Performance Analysis

In this Section, skipping the mathematical details about the signal transmission (the readers can refer to [1] for details), we analyze the achieved outage performance and diversity order of F-DF and S-DF protocols under the modified system framework.

For F-DF protocol, the SNR received from the m-th user at D can be written as [3]

$$\gamma_m^{\text{F-DF}} = \min\{\gamma_{S_mR}, \gamma_{S_mD} + \gamma_{RD}\}. \tag{1}$$

On the other hand, for S-DF protocol, the SNR received from the m-th user at D is given by [3]

$$\gamma_m^{\text{S-DF}} = \begin{cases} 2\gamma_{S_mD}, & \text{if } \gamma_{S_mR} < 2^{2\Re} - 1 \\ \gamma_{S_mD} + \gamma_{RD}, & \text{if } \gamma_{S_mR} > 2^{2\Re} - 1 \end{cases}, \tag{2}$$

with $\Re$ being the target end-to-end spectral efficiency in bps/Hz.

In MUD-based scheduling, the user who achieves the highest received SNR at D is selected and the end-to-end SNR satisfies $\gamma^{\text{F-DF}} = \max_m \gamma_m^{\text{F-DF}}$, for the F-DF protocol, and $\gamma^{\text{S-DF}} = \max_m \gamma_m^{\text{S-DF}}$, for the S-DF protocol. In what follows, the outage probabilities for these two protocols will be derived and discussed.

A. F-DF Protocol

Firstly, the outage probability can be expressed as

$$\begin{aligned} P_{\text{out}}^{\text{F-DF}} &= \Pr\left[\frac{1}{2}\log_2\left(1 + \gamma^{\text{F-DF}}\right) < \Re\right] \\ &= \Pr\left[\max_m \{\gamma_m^{\text{F-DF}}\} < 2^{2\Re} - 1 \triangleq \rho\right] \\ &= \Pr\left[\max_m \left\{\min\{\gamma_{S_mR}, \gamma_{S_mD} + \gamma_{RD}\}\right\} < \rho\right]. \end{aligned} \tag{3}$$

From the probability theory, (3) can be rewritten as

$$\begin{aligned} P_{\text{out}}^{\text{F-DF}} &= \int_0^\infty \Pr\left[\max_m \left\{\min\{\gamma_{S_mR}, \gamma_{S_mD} + y\}\right\} < \rho\right] \\ &\quad \times p_{\gamma_{RD}}(y)dy \\ &= \int_0^\infty \prod_{m=1}^M \underbrace{\Pr\left[\min\left\{\gamma_{S_mR}, \gamma_{S_mD} + y\right\} < \rho\right]}_{I_m} p_{\gamma_{RD}}(y)dy, \end{aligned} \tag{4}$$

where $p_X(\cdot)$ stands for the probability density function (PDF) of a random variable (RV) X and I_m can be expressed as

$$I_m = F_{\gamma_{S_mR}}(\rho) + \left(1 - F_{\gamma_{S_mR}}(\rho)\right)\Pr\left[\gamma_{S_mD} < \rho - y\right], \tag{5}$$

in which $F_X(\cdot)$ indicates the cumulative distribution function (CDF) of a RV X. From (5), note that for $y > \rho$, $\Pr[\gamma_{S_m D} < \rho - y] = 0$, whereas for $y \leq \rho$, $\Pr[\gamma_{S_m D} < \rho - y] = 1 - e^{-\lambda_{S_m D}(\rho - y)}$, where $\lambda_{S_m D} \triangleq 1/\mathrm{E}[\gamma_{S_m D}]$, with $\mathrm{E}[\cdot]$ denoting statistical average. Hence, it follows that

$$I_m = \begin{cases} 1 - e^{-\rho \lambda_{S_m R}}, & \text{if } y > \rho \\ 1 - e^{-\rho \lambda_{S_m R} - \lambda_{S_m D}(\rho - y)}, & \text{if } y \leq \rho \end{cases}, \tag{6}$$

where $\lambda_{S_m R} \triangleq 1/\mathrm{E}[\gamma_{S_m R}]$. By substituting (6) in (4), we arrive at

$$P_{\text{out}}^{\text{F-DF}} = \underbrace{\int_0^\rho \left[\prod_{m=1}^{M} \left(1 - e^{-\rho \lambda_{S_m R} - \lambda_{S_m D}(\rho - y)}\right)\right] \lambda_{RD} e^{-y\lambda_{RD}} dy}_{\psi} + \underbrace{\int_\rho^\infty \left[\prod_{m=1}^{M} \left(1 - e^{-\rho \lambda_{S_m R}}\right)\right] \lambda_{RD} e^{-y\lambda_{RD}} dy}_{\varphi}, \tag{7}$$

in which $\lambda_{RD} \triangleq 1/\mathrm{E}[\gamma_{RD}]$ and φ can be readily solved as

$$\varphi = \left[\prod_{m=1}^{M} \left(1 - e^{-\rho \lambda_{S_m R}}\right)\right] e^{-\rho \lambda_{RD}}. \tag{8}$$

Now, turning our attention for the derivation of ψ, $\prod_{m=1}^{M} \left(1 - e^{-\rho \lambda_{S_m R} - \lambda_{S_m D}(\rho - y)}\right)$ can be rewritten according to [12, Eq. (7)] as (9), given at the top of the next page. Substituting appropriately (9) into ψ and performing the required integral, a closed-form expression is attained so that $P_{\text{out}}^{\text{F-DF}}$ can be derived as

$$\begin{aligned} P_{\text{out}}^{\text{F-DF}} = &\left[\prod_{m=1}^{M} \left(1 - e^{-\rho \lambda_{S_m R}}\right)\right] e^{-\rho \lambda_{RD}} + \sum_{n=0}^{M} (-1)^{M-n} \\ &\times \sum_{\substack{1 \leq k_1 < \ldots < k_n \leq M \\ 1 \leq k_{n+1} < \ldots < k_M \leq M \\ k_1 \neq k_2 \neq \ldots \neq k_M}} e^{-\rho\left(\sum_{m=n+1}^{M}\left(\lambda_{S_{k_m} R} + \lambda_{S_{k_m} D}\right)\right)} \\ &\times \underbrace{\frac{\lambda_{RD}}{\lambda_{RD} - \sum_{m=n+1}^{M} \lambda_{S_{k_m} D}} \left(1 - e^{-\rho\left(\lambda_{RD} - \sum_{m=n+1}^{M} \lambda_{S_{k_m} D}\right)}\right)}_{\Xi}. \end{aligned} \tag{10}$$

Note that as $\bar{\gamma} \to \infty$ (or equivalently $\lambda \to 0$), Ξ can be asymptotically written as $\rho\lambda_{RD}$ and accordingly (10) can be approximated by

$$\begin{aligned} P_{\text{out}}^{\text{F-DF}} &\approx \left(\prod_{m=1}^{M} \rho\, \lambda_{S_m R}\right) + \rho\lambda_{RD} \sum_{n=0}^{M} (-1)^{M-n} \\ &\quad \times \sum_{\substack{1 \leq k_1 < \ldots < k_n \leq M \\ 1 \leq k_{n+1} < \ldots < k_M \leq M \\ k_1 \neq k_2 \neq \ldots \neq k_M}} e^{-\rho\left(\sum_{m=n+1}^{M}\left(\lambda_{S_{k_m} R} + \lambda_{S_{k_m} D}\right)\right)} \\ &\overset{(a)}{=} \left(\prod_{m=1}^{M} \rho\, \lambda_{S_m R}\right) + \rho\lambda_{RD} \prod_{m=1}^{M} \left[\rho\left(\lambda_{S_m R} + \lambda_{S_m D}\right)\right] \\ &\overset{(b)}{\simeq} \left(\frac{\rho}{\bar{\gamma}}\right)^M \prod_{m=1}^{M} \left(\frac{1}{P_{S_m} \mu_{S_m R}}\right), \end{aligned} \tag{11}$$

in which (a) arises from [12, Eq. (7)] and (b) is due to the fact that only the dominant term remains as $\bar{\gamma} \to \infty$. It is noteworthy that (11-b) is equivalent to [1, Eq. (12)] and the diversity order is still M even though the system framework is now different. However, as will be seen in the subsequent analysis for S-DF protocol, the diversity order under the modified system framework becomes different from that of [1]. This phenomenon happens due to the characteristic of the specific cooperative protocol.

B. S-DF Protocol

For S-DF protocol, the outage probability can be expressed as

$$\begin{aligned} P_{\text{out}}^{\text{S-DF}} &= \Pr\left[\frac{1}{2}\log_2\left(1 + \gamma^{\text{S-DF}}\right) < \Re\right] \\ &= \Pr\left[\max_m \left\{\gamma_m^{\text{S-DF}}\right\} < \rho\right]. \end{aligned} \tag{12}$$

From the probability theory, (12) can be rewritten as

$$P_{\text{out}}^{\text{S-DF}} = \int_0^\infty \left[\prod_{m=1}^{M} \underbrace{\Pr\left[\gamma_m^{\text{S-DF}} < \rho | \gamma_{RD} = y\right]}_{\tau_m}\right] p_{\gamma_{RD}}(y) dy, \tag{13}$$

where τ_m is given by

$$\begin{aligned} \tau_m = &\Pr\left[\gamma_{S_m R} < \rho\right] \Pr\left[\gamma_{S_m D} < \frac{\rho}{2}\right] \\ &+ \Pr\left[\gamma_{S_m R} \geq \rho\right] \Pr\left[\gamma_{S_m D} < \rho - y\right]. \end{aligned} \tag{14}$$

Now, relying on the relation between ρ and y, τ_m can be further written as

$$\tau_m = \begin{cases} \left(1 - e^{-\rho\lambda_{S_m R}}\right)\left(1 - e^{-(\rho/2)\lambda_{S_m D}}\right), & \text{if } y > \rho \\ \left(1 - e^{-\rho\lambda_{S_m R}}\right)\left(1 - e^{-(\rho/2)\lambda_{S_m D}}\right) \\ +e^{-\rho\lambda_{S_m R}}\left(1 - e^{-(\rho - y)\lambda_{S_m D}}\right), & \text{if } y \leq \rho \end{cases}. \tag{15}$$

By substituting (15) into (13), it follows (16), from which it is easy to arrive at

$$\Phi = \left[\prod_{m=1}^{M} \left(1 - e^{-\rho\lambda_{S_m R}}\right)\left(1 - e^{-(\rho/2)\lambda_{S_m D}}\right)\right] e^{-\rho\lambda_{RD}}. \tag{17}$$

Invoking [12, Eq. (7)] again, ξ in (16) can be reformulated as

$$\begin{aligned} \xi = &\sum_{n=0}^{M} \sum_{\substack{1 \leq k_1 < \ldots < k_n \leq M \\ 1 \leq k_{n+1} < \ldots < k_M \leq M \\ k_1 \neq k_2 \neq \ldots \neq k_M}} \\ &\times \prod_{m=1}^{n} \left[\left(1 - e^{-\rho\lambda_{S_{k_m} R}}\right)\left(1 - e^{-(\rho/2)\lambda_{S_{k_m} D}}\right) + e^{-\rho\lambda_{S_{k_m} R}}\right] \\ &\times \prod_{m=n+1}^{M} \left[(-1) e^{-\rho\left(\lambda_{S_{k_m} R} + \lambda_{S_{k_m} D}\right) + y\lambda_{S_{k_m} D}}\right]. \end{aligned} \tag{18}$$

Finally, by plugging (17) and (18) into (16) and after some arrangements, we arrive at a closed-form expression for $P_{\text{out}}^{\text{S-DF}}$

$$\prod_{m=1}^{M}\left(1-e^{-\rho\,\lambda_{S_mR}-\lambda_{S_mD}(\rho-y)}\right)=\sum_{n=0}^{M}\sum_{\substack{1\le k_1<\ldots<k_n\le M\\1\le k_{n+1}<\ldots<k_M\le M\\k_1\neq k_2\neq\ldots\neq k_M}}\prod_{m=n+1}^{M}\left(-e^{-\rho\,\lambda_{S_{k_m}R}-\lambda_{S_{k_m}D}(\rho-y)}\right)$$
$$=\sum_{n=0}^{M}(-1)^{M-n}\sum_{\substack{1\le k_1<\ldots<k_n\le M\\1\le k_{n+1}<\ldots<k_M\le M\\k_1\neq k_2\neq\ldots\neq k_M}} e^{y\left(\sum_{m=n+1}^{M}\lambda_{S_{k_m}D}\right)-\rho\left(\sum_{m=n+1}^{M}\left(\lambda_{S_{k_m}R}+\lambda_{S_{k_m}D}\right)\right)}. \quad (9)$$

$$P_{\text{out}}^{\text{S-DF}}=\underbrace{\int_0^{\rho}\left(\prod_{m=1}^{M}\left[\left(1-e^{-\rho\lambda_{S_mR}}\right)\left(1-e^{-(\rho/2)\lambda_{S_mD}}\right)+e^{-\rho\lambda_{S_mR}}\left(1-e^{-(\rho-y)\lambda_{S_mD}}\right)\right]\right)}_{\xi}\lambda_{RD}\,e^{-y\lambda_{RD}}dy$$
$$+\underbrace{\int_{\rho}^{\infty}\left[\prod_{m=1}^{M}\left(1-e^{-\rho\lambda_{S_mR}}\right)\left(1-e^{-(\rho/2)\lambda_{S_mD}}\right)\right]\lambda_{RD}\,e^{-y\lambda_{RD}}dy}_{\Phi}. \quad (16)$$

as

$$P_{\text{out}}^{\text{S-DF}}=\left[\prod_{m=1}^{M}\left(1-e^{-\rho\lambda_{S_mR}}\right)\left(1-e^{-(\rho/2)\lambda_{S_mD}}\right)\right]e^{-\rho\lambda_{RD}}$$
$$+\sum_{n=0}^{M}\sum_{\substack{1\le k_1<\ldots<k_n\le M\\1\le k_{n+1}<\ldots<k_M\le M\\k_1\neq k_2\neq\ldots\neq k_M}}$$
$$\times\prod_{m=1}^{n}\left[\left(1-e^{-\rho\lambda_{S_{k_m}R}}\right)\left(1-e^{-(\rho/2)\lambda_{S_{k_m}D}}\right)+e^{-\rho\lambda_{S_{k_m}R}}\right]$$
$$\times\prod_{m=n+1}^{M}\left[(-1)e^{-\rho\left(\lambda_{S_{k_m}R}+\lambda_{S_{k_m}D}\right)}\right]$$
$$\times\underbrace{\frac{\lambda_{RD}\left(1-e^{-\rho\left(\lambda_{RD}-\sum_{m=n+1}^{M}\lambda_{S_{k_m}D}\right)}\right)}{\lambda_{RD}-\sum_{m=n+1}^{M}\lambda_{S_{k_m}D}}}_{\Theta}. \quad (19)$$

For sufficiently high SNR, i.e., $\bar{\gamma}\to\infty$, Θ can be asymptotically expressed as $\rho\lambda_{RD}$. Consequently, (19) can be reformulated as (20), given at the top of the next page, where (c) is due to [12, Eq. (7)] and (d) holds because only the dominant term remains as $\bar{\gamma}\to\infty$. From (20-d), it can be noticed that the diversity order of the S-DF protocol changes from $2M$ [1] to $M+1$ under the considered system framework.

IV. Numerical Examples and Discussions

In this Section, we compare the outage probability of the F-DF and S-DF protocols under the original and modified system frameworks. All analytical results have been validated through simulations. Similar to [1], we consider a symmetric scenario, where each link undergoes identical fading statistics and each transmitter possesses the same transmit power, i.e., $\mu_{S_mD}=\mu_{S_mR}=\mu_{RD}=1$ and $P_{S_m}=P_R=1$. Without loss of generality, we assume $\Re=1$ in all the cases considered.

Fig. 1 depicts the outage behavior of the F-DF protocol in the original and modified system frameworks. First of all, it can be seen that the exact analytical results match very well with the simulations and the asymptotes are tight bounds in the medium and high SNR regions. It is also observed that for F-DF protocol, the outage performance does not change considerably under the modified system framework in comparison with that under the original one. However, the performance gap tends to enlarge with an increase of M. Besides, the diversity order remains being equal to M under the two system frameworks as predicted by our analytical results.

Fig. 2 shows the outage probability of the S-DF protocol under the two system frameworks. Although the obtained asymptotes are not tight bounds, they are in parallel with the corresponding simulated results in high SNR regime, which corroborates the presented diversity analysis. Furthermore, the achieved outage performance and diversity order decreases in the modified system model, as expected.

V. Conclusions

In this paper, based on [1], we proposed a modified system framework for multiuser diversity in multiuser two-hop cooperative relay wireless networks. Under the new system framework, we analyzed the achieved outage probability and diversity order. In particular, two closed-from expressions were derived for the outage probability of F-DF and S-DF protocols, from which the asymptotic analysis is performed. It is shown that the achieved diversity order of F-DF protocol is still M, whereas the diversity order of S-DF protocol changes from $2M$ to $M+1$ in the new system framework. These new results allow us to say that, for single-relay MUD-based cooperative network, the obtained improvement in terms of diversity order is very limited compared with the counterpart without relay.

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\begin{aligned}
P_{\text{out}}^{\text{S-DF}} \approx & \prod_{m=1}^{M} (\rho^2/2)\lambda_{S_m R}\lambda_{S_m D} + \rho\lambda_{RD} \sum_{n=0}^{M} \sum_{\substack{1\le k_1<\ldots<k_n\le M \\ 1\le k_{n+1}<\ldots<k_M\le M \\ k_1\neq k_2\neq\ldots\neq k_M}} \prod_{m=1}^{n} \left[\left(1-e^{-\rho\lambda_{S_{k_m}R}}\right)\left(1-e^{-(\rho/2)\lambda_{S_{k_m}D}}\right)+e^{-\rho\lambda_{S_{k_m}R}}\right] \\
& \times \prod_{m=n+1}^{M} \left[(-1)e^{-\rho(\lambda_{S_{k_m}R}+\lambda_{S_{k_m}D})}\right] \qquad (20) \\
& \overset{(c)}{=} \prod_{m=1}^{M} (\rho^2/2)\lambda_{S_m R}\lambda_{S_m D} + \rho\lambda_{RD} \prod_{m=1}^{M} \left[\left(1-e^{-\rho\lambda_{S_m R}}\right)\left(1-e^{-(\rho/2)\lambda_{S_m D}}\right)+e^{-\rho\lambda_{S_m R}}-e^{-\rho(\lambda_{S_m R}+\lambda_{S_m D})}\right] \\
& \overset{(d)}{\simeq} \left(\frac{\rho}{\bar{\gamma}}\right)^{M+1} \frac{1}{P_R\,\mu_{RD}} \prod_{m=1}^{M} \left(\frac{1}{\mu_{S_m D}}\right).
\end{aligned}
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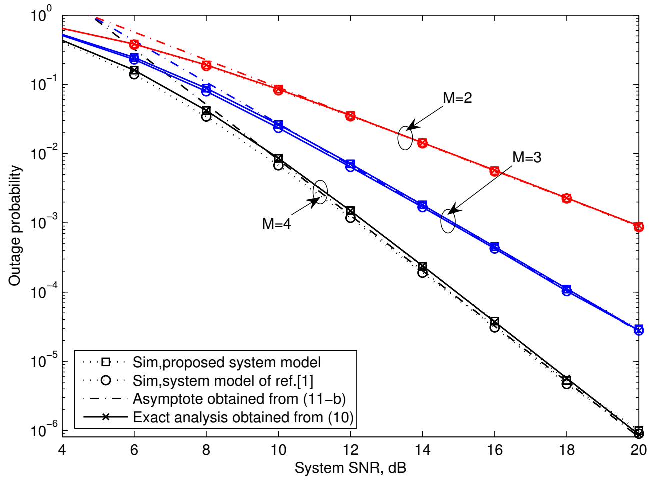

Fig. 1. Outage probability versus system SNR for F-DF protocol under different system frameworks.

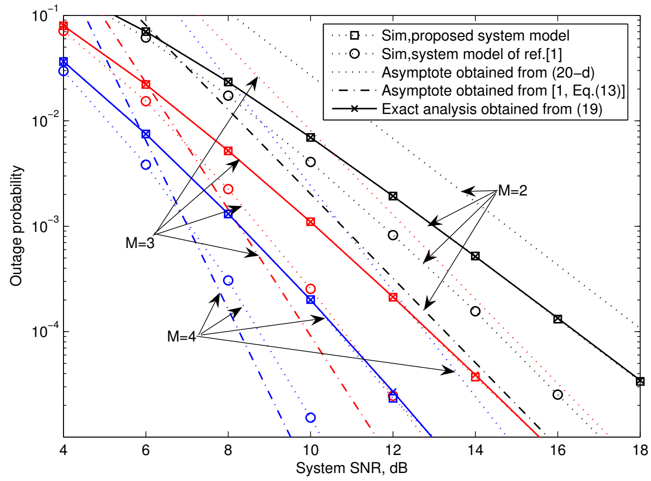

Fig. 2. Outage probability versus system SNR for S-DF protocol under different system frameworks.

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