Sequential Relay Selection in D2D-Enabled Cellular Networks With Outdated CSI Over Mixed Fading Channels

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***Abstract*—The impact of outdated channel state information on two sequential relay selection schemes for device-to-device underlaid cellular networks over mixed fading channels is investigated. To this end, the mutual outage probability (MOP) is analyzed in which an easy-to-evaluate analytical expression for the MOP is derived. Moreover, an asymptotic analysis of the MOP at high signal-to-noise ratio is provided, and the diversity order is evaluated.**

***Index Terms*—Cellular network, D2D communication, mixed fading, mutual outage probability, outdated CSI.**

I. Introduction

RELAY-AIDED underlay inband device-to-device (D2D) communication in cellular networks [1] has recently attracted a great deal of attention. From a physical-layer (PHY) security perspective, the interference issue inherent to such networks can be advantageous and exploited as a friendly jamming signal to prevent wiretapping [2]. Unlike a conventional jammer which consumes its power merely on interfering with the eavesdropper, D2D communication is able to achieve its own transmission at the same time yielding a win-win situation for the cellular network and D2D links in terms of security provisioning and high spectral efficiency, respectively.

In [1], a full-duplex (FD) orthogonal frequency-division multiplexing (OFDM) D2D dual-hop system where multiple FD relays assist the device transmitter was investigated assuming non-security requirements. The impact of interference and outdated CSI on the performance of a vehicle-to-vehicle (V2V) cooperative relaying system was studied in [3]. Despite the popularity of relay-aided D2D-enabled cellular networks, providing wireless secure transmissions for the cellular network and throughput improvement for D2D communication concurrently has not yet been investigated in the open literature. In this letter, we propose two sequential relay selection strategies in D2D-assisted cellular network with the aim of providing wireless security for the cellular network as well as throughput enhancement for the D2D communication. In particular, we investigate the impact of outdated channel state information (CSI) on the performance of the underlying system assuming that both networks experience different fading models. To this end, an analytical expression for the mutual outage probability (MOP) which assesses the cooperation between the two networks is presented. Furthermore, an asymptotic analysis of the MOP at high signal-to-noise (SNR) is derived, which gives some insights into the effect of the key system parameters on the proposed scheme.

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II. System and Channel Models

We consider a scenario with multiple uplink transmissions among L cellular users (CUs) and one base station (BS), in which each CU transmits on a dedicated channel in the presence of a passive eavesdropper (PE). Both the BS and the PE optimally combine the received signals from the L CUs using a maximal-ratio combiner in an effort to maximize the probability of secure transmission and eavesdropping, respectively. Meanwhile, a D2D system which consists of one device transmitter (DT), one device receiver (DR) and N D2D relays is allowed to reuse the CU channels for its own communication.[1] It is assumed that all nodes are equipped with a single antenna, and there is no direct communication between DT and DR due to shadowing.[2] Moreover, the BS has full knowledge of all the channel statistics and the channels in the cellular network experience η–μ fading, while the D2D links are subject to Rayleigh fading.[3] Such mixed fading scenario is suitable to model real urban microcell and indoor wireless environments [6].

The D2D transmissions occur in two time slots while the cellular transmissions take place in only one time slot. Both the D2D and cellular transmissions are assumed to be well synchronized. In the first time slot, DT transmits to all the relays by reusing channels allocated to the CUs, while all the CUs remain silent with the aim of acquiring in return a higher security for their transmissions by the D2D communication in the next time slot. The above-mentioned scenario

[1]It is worthwhile to note that the PE is part of the cellular network and can be distinguishable from the D2D pairs (i.e., DT or DR) or the relay devices.

[2]In practice, a strong direct link might not be feasible due to shadowing stemming from the presence of physical obstacles. Recently, relay-based D2D communications systems (see [4] and the references therein) have been proposed as a means to overcome the shadowing issues and to extend coverage.

[3]The assumption of Rayleigh faded D2D links has been widely adopted in numerous previous works (see, for instance, [2], [5] and references therein), while the choice of the η-μ distribution to model the cellular link propagation is motivated by the fact it can accurately model small-scale variations of the fading signal under non-line-of-sight (NLOS) conditions.

provides mutual benefits for both the CU network and the D2D system. The received signals at the n^{th} relay is given by $y_{R_n} = \sqrt{P_t} f_n s + z_{R_n}$, where P_t is the transmit power at DT, f_n is the channel gain of the DT–R_n link, s is the transmitted signal, and z_{R_n} is the additive white Gaussian noise (AWGN) with zero mean and variance σ^2. All the relays attempt to decode the received signal, and only the ones that successfully estimate the transmitted signal form a decoding set. A single relay, denoted by R_θ, is chosen from the decoding set to forward the signal to DR in the second time slot. The received signal at DR is given by $y_{\text{DR}} = \sqrt{P_{R_\theta}} g_{R_\theta} \hat{s} + \sum_{k=1}^{L} \sqrt{P_{\text{cu}_k}} d_k x_k + z_{\text{DR}}$, where P_{cu_k} and P_{R_θ} are the transmit powers at CU_k and R_θ, respectively, g_{R_θ} and d_k are the channel gains of the R_θ–DR link and the CU_k–DR link, respectively, $\hat{s}$ is the estimated source signal, z_{DR} is the zero-mean AWGN with variance σ^2, and R_θ represents the best relay which is selected based on the following criterion

$$R_\theta = \arg\max_{j \in \mathcal{D}_s} \{\hat{\gamma}_{j,\text{DR}}\}, \tag{1}$$

with $\mathcal{D}_s$ denoting the decoding set, $\hat{\gamma}_{j,\text{DR}} = \frac{P_{R_j}}{\sigma^2} |\hat{g}_j|^2$ and $\hat{g}_j$ is the outdated channel gain of the R_j–DT link. In (1), $\hat{\gamma}_{j,\text{DR}}$ denotes the SNR at the time of selection and may differ from the actual SNR, denoted by $\gamma_{j,\text{DR}}$, at the transmission instant due to mobility and feedback delay. The relationship between the actual channel gain g_j and the outdated one $\hat{g}_j$ can be expressed as $g_j = \sqrt{\rho_1} \hat{g}_j + \sqrt{1-\rho_1} u_j$, where ρ_1 denotes the correlation coefficient between g_j and $\hat{g}_j$ with $0 \le \rho_1 \le 1$, and u_j is a circularly complex Gaussian random variable (RV) having the same variance as $\hat{g}_j$. In the meantime, the L CUs transmit to the BS while the PE attempts to intercept the transmissions. The received signals at the BS and the PE can be written as $y_{\text{BS}} = \sum_{k=1}^{L} \sqrt{P_{\text{cu}_k}} h_k x_k + \sqrt{P_{R_\psi}} b_{R_\psi} \hat{s} + z_{\text{BS}}$ and $y_{\text{PE}} = \sum_{k=1}^{L} \sqrt{P_{\text{cu}_k}} e_k x_k + \sqrt{P_{R_\psi}} c_{R_\psi} \hat{s} + z_{\text{PE}}$, where P_{R_ψ} represents the transmitted power at the relay R_ψ, x_k is the transmitted signal from the k^{th} CU, h_k, e_k, b_{R_ψ} and c_{R_ψ} stand for the channel gains of the CU_k–BS, CU_k–PE, R_ψ–BS and R_ψ–PE links, respectively, z_{BS} and z_{PE} are the zero-mean AWGN with variance σ^2 at BS and PE, respectively. In the sequel, it is assumed that all the CUs transmit with the same power P_{cu}, and for the sake of easy notation, the subscripts b and c will be used in place of b_{R_ψ} and c_{R_ψ}, respectively. Given that the cellular transmissions to the BS experience η–μ fading [7] and are optimally combined, the probability density function (PDF) of the SNR at the receiver's combiner output can be obtained with the help of [7] and [8, eq. (8.445.1)], and is given by

$$f_{\gamma_h}(x) = \frac{2\sqrt{\pi}\hbar_h^{L\mu_i}}{\Gamma(L\mu_h)} \exp\left(-\frac{2\mu_h \hbar_h x}{\bar{\gamma}_h}\right) \times \sum_{k=0}^{\infty} \frac{H_h^{2k} \mu_h^{2L\mu_h+2k}}{k!\Gamma(L\mu_h+k+0.5)} \frac{x^{2L\mu_h+2k-1}}{\bar{\gamma}_h^{2L\mu_h+2k}}, \tag{2}$$

where $\gamma_h = \sum_{k=1}^{L} \gamma_{h_k} = \frac{P_{\text{cu}}}{\sigma^2} \sum_{k=1}^{L} |h_k|^2$, $\Gamma(\cdot)$ is the Gamma function, $\bar{\gamma}_h = \mathbb{E}\{\gamma_h\}$ denotes the average SNR, with $\mathbb{E}\{\cdot\}$ denoting expectation, and μ_h represents the number of multipath clusters. From (2), the cumulative distribution function (CDF) can be expressed as

$$F_{\gamma_h}(x) = \frac{\sqrt{\pi}}{\Gamma(L\mu_h)} \sum_{k=0}^{\infty} \frac{H_h^{2k} 2^{-2L\mu_h-2k+1}}{k!\Gamma(L\mu_h+k+0.5)\hbar_h^{L\mu_h+2k}} \times \Upsilon\left(2L\mu_h+2k, \frac{2\mu_h\hbar_h x}{\bar{\gamma}_h}\right), \tag{3}$$

where $\Upsilon(\cdot,\cdot)$ denotes the lower incomplete Gamma function [8, eq. (8.350.1)]. Both $\hbar_h$ and H_h are dependent of η_h and can be given in two formats (please, see [7] for details).

III. Mutual Outage Probability Analysis

The MOP can describe the mutual cooperation between the D2D communication and cellular network and is defined as the probability that either of the rate associated with any of the two systems falls below its corresponding predefined rate [9]. It can be expressed mathematically as $\text{MOP} = \mathbb{P}\{\gamma_{\text{BS}} < \gamma_S$ or $\gamma_{\text{e2e}} < \gamma_{\text{T}}\}$, where $\gamma_S = 2^{R_S} - 1$ is the secrecy threshold, R_S is the secrecy rate, $\gamma_{\text{T}} = 2^{R_{\text{T}}} - 1$ is the specified secondary threshold with R_{T} denoting the secondary threshold rate and R_{T} not necessarily equal to R_S, γ_{e2e} is the end-to-end secondary signal-plus-interference-to-noise ratio (SINR), and $\mathbb{P}\{\cdot\}$ denotes probability. Since the RVs γ_{BS} and γ_{e2e} are independent, the above-mentioned MOP expression can further be expressed as

$$\text{MOP} = F_{\gamma_{\text{BS}}}(\gamma_S) + F_{\gamma_{\text{e2e}}}(\gamma_{\text{T}}), \tag{4}$$

where $F_X(x)$ means the CDF of the RV *X*.

A. Exact MOP

From the y_{BS} expression, note that in the cellular network there is interference affecting the cellular transmissions, which can be beneficial from the information-theoretic viewpoint, and can be used to mainly confound the eavesdropper.[4] The selection criterion adopted from [10] can be defined as

$$R_\psi = \arg\max_{j\in\mathcal{R}} \left\{1 + \frac{\sum_{k=1}^{L} \gamma_{h_k}}{1+\hat{\gamma}_{b_j}}\right\} = \arg\min_{j\in\mathcal{R}} \hat{\gamma}_{b_j}, \tag{5}$$

where $\mathcal{R} = N - \{R_\theta\}$ represents the set of relays that have not been selected for the transmission to DR in the second time slot, and $\hat{\gamma}_{b_j} = \frac{P_{R_j}}{\sigma^2} |\hat{b}_j|^2$ is the SNR at the time of selection, which may differ from the actual SNR at the transmission instant, denoted by γ_{b_j}. The relationship between the actual channel gain b_j and the outdated one $\hat{b}_j$ is given by $b_j = \sqrt{\rho_2} \hat{b}_j + \sqrt{1-\rho_2} w_j$, where ρ_2 is the correlation coefficient between b_j and $\hat{b}_j$, with $0 \le \rho_2 \le 1$, and w_j is a circularly complex Gaussian RV having the same variance as b_j. From y_{BS}, the SINR can be expressed as $\gamma_{\text{BS}} = \frac{\gamma_h}{1+\gamma_b}$, and based on probability theory, the CDF of γ_{BS} can be evaluated as

$$F_{\gamma_{\text{BS}}}(x) = \int_0^\infty F_{\gamma_h}(x(1+y)) f_{\gamma_b}(y) \mathrm{d}y, \tag{6}$$

which requires the determination of the PDF $f_{\gamma_b}(\cdot)$. In (6), the PDF of the actual γ_b at the transmission instant is given by

$$f_{\gamma_b}(x) = \int_0^\infty f_{\gamma_b|\hat{\gamma}_b}(x|y) f_{\hat{\gamma}_b}(y) \mathrm{d}y, \tag{7}$$

[4] It is worth mentioning that ideally, such an interference should only affect the eavesdropper. However, in practical setups, the BS and PE can be in close range and therefore both will be affected by the same interfering source.

$$F_{\gamma_{\mathrm{BS}}}(\gamma_S) = \frac{M\sqrt{\pi}}{\Gamma(L\mu_h)\bar{\gamma}_b(\rho_2+M(1-\rho_2))}\sum_{k=0}^{\infty}\left(\frac{\Gamma(2L\mu_h+2k)H_h^{2k}2^{-2L\mu_h-2k+1}}{k!\Gamma(L\mu_h+k+0.5)\hbar_h^{L\mu_h+2k}}\right)\Bigg\{\frac{\bar{\gamma}_b(\rho_2+M(1-\rho_2))}{M} - \sum_{m=0}^{2L\mu_h+2k-1} \frac{\gamma_S^m}{m!}\left(\frac{2\mu_h\hbar_h}{\bar{\gamma}_h}\right)^m \Bigg(\underbrace{\frac{M}{\bar{\gamma}_b(\rho_2+M(1-\rho_2))}+\frac{2\mu_h\hbar_h\gamma_S}{\bar{\gamma}_h}}_{\Delta}\Bigg)^{-(m+1)} \exp\left(\frac{M}{\bar{\gamma}_b(\rho_2+M(1-\rho_2))}\right)\Gamma(m+1,\Delta)\Bigg\} \quad (11)$$

$$F_{\gamma_{RD}^{\mathrm{eff}}}(x) = l\sum_{m=0}^{l-1}\binom{l-1}{m}\frac{(-1)^m}{m+1}\Bigg\{1-\frac{2\sqrt{\pi}\hbar_d^{L\mu_d}}{\Gamma(L\mu_d)}\exp\left(-\frac{(m+1)x}{\bar{\gamma}_{RD}(1+m(1-\rho_1))}\right)\sum_{k=0}^{\infty}\frac{H_d^{2h}\mu_d^{2L\mu_d+2k}\Gamma(2L\mu_d+2k)}{k!\Gamma(L\mu_d+k+0.5)\bar{\gamma}_d^{2L\mu_d+2k}} \times \left(\frac{2\mu_d\hbar_d}{\bar{\gamma}_d}+\frac{(m+1)x}{\bar{\gamma}_{RD}(1+m(1-\rho_1))}\right)^{-(2L\mu_d+2k)}\Bigg\}. \quad (15)$$

where the conditional PDF $f_{\gamma_b|\hat{\gamma}_b}(x|y)$ can be expressed as

$$f_{\gamma_b|\hat{\gamma}_b}(x|y) = \lambda\exp\left(\frac{-(\rho_2 y+x)}{(1-\rho_2)\bar{\gamma}_b}\right)I_0\left(\frac{2\sqrt{\rho_2 xy}}{(1-\rho_2)\bar{\gamma}_b}\right), \quad (8)$$

with $\lambda = \frac{1}{(1-\rho_2)\bar{\gamma}_b}$, $I_0(\cdot)$ denoting the modified Bessel function of the first kind and zeroth order. Also, in (5), the selection is equivalent to the worst relay selection so that the PDF of $\hat{\gamma}_b$ can be given by

$$f_{\hat{\gamma}_b}(x) = \frac{M}{\bar{\gamma}_b}\exp\left(-\frac{Mx}{\bar{\gamma}_b}\right), \quad (9)$$

where $M = \mathrm{N}-1$. By substituting (8) and (9) in (7) and with the help of [8, eqs. (6.614.3), (9.220.2), and (9.215)], and after some algebraic manipulations, we get

$$f_{\gamma_b}(x) = \frac{1}{\bar{\gamma}_b(\rho_2+M(1-\rho_2))}\exp\left(\frac{-Mx}{\bar{\gamma}_b(\rho_2+M(1-\rho_2))}\right). \quad (10)$$

Now, by plugging (3) and (10) into (6), and with the help of [8, eqs. (8.352.1) and (3.382.4)] and many algebraic manipulations, an analytical expression for the CDF of γ_{BS} can be obtained as in (11), shown at the top of this page, with $\Gamma(\cdot,\cdot)$ denoting the upper incomplete Gamma function [8, eq. (8.350.2)]. Next, we evaluate the CDF of γ_{e2e} which in its general form can be written as

$$F_{\gamma_{\mathrm{e2e}}}(\gamma_{\mathrm{T}}) = \left(F_{\gamma_{SR}}(\gamma_{\mathrm{T}})\right)^N + \sum_{l=1}^{N}\binom{N}{l}\left(F_{\gamma_{SR}}(\gamma_{\mathrm{T}})\right)^{N-l} \times \left(1-F_{\gamma_{SR}}(\gamma_{\mathrm{T}})\right)^l F_{\gamma_{RD}^{\mathrm{eff}}}(\gamma_{\mathrm{T}}). \quad (12)$$

In order to evaluate (12), the CDFs of γ_{SR} and $\gamma_{RD}^{\mathrm{eff}}$ are required. The expression of the former can easily be obtained as $F_{\gamma_{SR}}(\gamma_{\mathrm{T}}) = 1-\exp(-\frac{\gamma_{\mathrm{T}}}{\bar{\gamma}_{SR}})$, where $\bar{\gamma}_{SR}$ is the average SNR of the channel between DT and a D2D relay. However, the derivation of the CDF of $\gamma_{RD}^{\mathrm{eff}}$ is a bit more involving. Knowing that $\gamma_{RD}^{\mathrm{eff}} = \frac{\gamma_{\mathrm{DR}}^{R_\theta}}{1+\gamma_d}$, where $\gamma_d = \sum_{k=1}^{L}\gamma_{d_k}$, from probability theory, $F_{\gamma_{RD}^{\mathrm{eff}}}(\gamma_{\mathrm{T}})$ can be evaluated as

$$F_{\gamma_{RD}^{\mathrm{eff}}}(\gamma_{\mathrm{T}}) = \int_0^{\infty}F_{\gamma_{RD}^{R_\theta}}(\gamma_{\mathrm{T}}(1+y))f_{\gamma_d}(y)\mathrm{d}y. \quad (13)$$

To obtain the CDF of $\gamma_{RD}^{R_\theta}$, which corresponds to the best relay in the D2D communication, we use a similar approach to that used to derive (10), which yields

$$F_{\gamma_{RD}^{R_\theta}}(y) = l\sum_{m=0}^{l-1}\binom{l-1}{m}\frac{(-1)^m}{m+1} \times \left\{1-\exp\left(-\frac{(m+1)y}{\bar{\gamma}_{RD}(1+m(1-\rho_1))}\right)\right\}. \quad (14)$$

Upon substituting (2) (with the subscript *h* and *d* interchanged) and (14) into (13), and with the help of [8, eq. (3.382.4)], and after some algebraic manipulations, $F_{\gamma_{RD}^{\mathrm{eff}}}(x)$ can be obtained as shown in (15), at the top of this page. Finally, plugging (15) and the aforementioned expression of $F_{\gamma_{SR}}(\gamma_{\mathrm{T}})$ into (12), and together with (11) into (4), the MOP is attained. Although such an expression is not given in closed-form, the derived series is steadily convergent and requires around 20 terms to achieve precise results. In addition, the derived exact MOP can be easily implemented in most popular computer softwares, such as MATHEMATICA.

B. Asymptotic MOP

Now, the asymptotic behavior of the MOP is investigated. Firstly, we start with the asymptotic expression of $F_{\gamma_{\mathrm{BS}}}(\gamma_S)$. As $\bar{\gamma}_h = \bar{\gamma} \to \infty$, (3) is dominated by the term corresponding to $k = 0$. With the approximation $\Upsilon(s,x) \approx \frac{x^s}{s}$ ($x \to 0$), (3) can be reduced to $F_{\gamma_h}^{\infty}(x) \approx \frac{\mathcal{G}1x^{2L\mu_h}}{\bar{\gamma}^{2L\mu_h}}$, where $\mathcal{G}_1 = \frac{\sqrt{\pi}\hbar_h^{L\mu_h}\mu_h^{2L\mu_h-1}}{L\Gamma(L\mu_h)\Gamma(L\mu_h+0.5)}$. Substituting (10) and the abovementioned expression $F_{\gamma_h}^{\infty}(x)$ in (6) and after performing some algebraic manipulations, (11) can be approximated by $F_{\gamma_{\mathrm{BS}}}^{\infty}(\gamma_S) \approx (\mathcal{G}_1\beta^{-1}\gamma_S^{2L\mu_h}e^{\beta}\mathrm{Ei}(-2L\mu_h,\beta))\bar{\gamma}^{-2L\mu_h}$, where $\beta = \bar{\gamma}_b(\rho_2+M(1-\rho_2))$ and $\mathrm{Ei}(\cdot)$ is the exponential integral defined in [8, eq. (8.211.1)].

Next, we focus on the high-SNR approximation of (15). Since the relay selection in the D2D communications is based on the nature of the CSI, the analysis consider two scenarios: outdated CSI ($0 \le \rho_1 < 1$) and perfect CSI ($\rho_1 = 1$), and it is assumed that $\bar{\gamma}_{SR} = \bar{\gamma}_{RD} = \bar{\gamma} \to \infty$ for the abovecited scenarios. Under the latter assumption, (12) reduces to $F^{\infty}_{\gamma_{e2e}}(\gamma_{\mathrm{T}}) \approx \sum_{l=1}^{N}\binom{N}{l}F_{\gamma^{\mathrm{eff}}_{RD}}(\gamma_{\mathrm{T}})$. Considering perfect CSI, with the help of $I_v(z) = \pi(z/2)^v\, G^{1,0}_{1,3}(\frac{z^2}{4}|^{\frac{1}{2}}_{0,-v,\frac{1}{2}})$, the binomial expansion $(1+a)^b = \sum_{j=0}^{b}\binom{b}{j}a^j$, and [11, eq. (2.24.3.1)], and after tedious manipulations, (12) can be approximated by

$$F^{\infty}_{\gamma_{\mathrm{e2e}}}(\gamma_{\mathrm{T}}) \approx \frac{\Theta\gamma_{\mathrm{T}}^{N}}{\bar{\gamma}^{N}}\left(\frac{\mu_d}{\bar{\gamma}_d}\right)^{L\mu_d-\frac{1}{2}}\sum_{j=0}^{N}\binom{N}{j}\left(\frac{\bar{\gamma}_d}{\mu_d\hbar_d}\right)^{2L\mu_d+j} \times G^{1,2}_{2,3}\left(\left(\frac{H_d}{\hbar_d}\right)^2 \middle| \begin{matrix} \frac{1-(2L\mu_d+j)}{2}, \frac{2-(2L\mu_d+j)}{2} \\ 0, -L\mu_d+\frac{1}{2}, \frac{1}{2}\end{matrix}\right), \quad (16)$$

where $\Theta = \frac{\pi\mu_d^{L\mu_d+\frac{1}{2}}\hbar_d^{L\mu_d}}{\Gamma(L\mu_d)\bar{\gamma}_d^{L\mu_d+\frac{1}{2}}}$ and $G^{m,n}_{p,q}(\cdot|^{\cdot}_{\cdot})$ is the Meijer G-function defined in [8, eq. (9.301)].

Similarly, assuming outdated CSI, (12) is approximated by

$$F^{\infty}_{\gamma_{\mathrm{e2e}}}(\gamma_{\mathrm{T}}) \approx \frac{N\Theta\gamma_{\mathrm{T}}}{\bar{\gamma}}\left(\sum_{m=0}^{N}\binom{N-1}{m}\frac{(-1)^m}{1+m(1-\rho_1)}\right) \times \left(\frac{\mu_d}{\bar{\gamma}_d}\right)^{L\mu_d-\frac{1}{2}}\sum_{j=0}^{1}\binom{1}{j}\left(\frac{\bar{\gamma}_d}{\mu_d\hbar_d}\right)^{2L\mu_d+j} \times G^{1,2}_{2,3}\left(\left(\frac{H_d}{\hbar_d}\right)^2 \middle| \begin{matrix} \frac{1-(2L\mu_d+j)}{2}, \frac{2-(2L\mu_d+j)}{2} \\ 0, -L\mu_d+\frac{1}{2}, \frac{1}{2}\end{matrix}\right). \quad (17)$$

Remark 1: The asymptotic MOP for any arbitrary value of ρ_2 and $\rho_1 = 1$ is given by using the derived $F^{\infty}_{\gamma_{\mathrm{BS}}}(\gamma_S)$ and (16) in (4), and the diversity order is given by $\mathcal{G}_{d_1} = \min(2L\mu_h, N)$.

Remark 2: The asymptotic MOP for any arbitrary value of ρ_2 and $0 \le \rho_1 < 1$ is given by using the derived $F^{\infty}_{\gamma_{\mathrm{BS}}}(\gamma_S)$ and (17) in (4), and the diversity order is given by $\mathcal{G}_{d_2} = \min(2L\mu_h, 1)$.

IV. Numerical Results and Discussions

Without loss of any generality, in this section we assume the following parameters: $\eta_h = 1.5$, $\mu_h = 0.5$, $\eta_d = 0.5$, $\mu_d = 8$, $\bar{\gamma}_{SR} = \bar{\gamma}_{RD} = \bar{\gamma}_h = \bar{\gamma}$, $\bar{\gamma}_d = \bar{\gamma}_b = 10$ dB, and $R_S = R_{\mathrm{T}} = 1$ bit/s/Hz. Fig. 1 shows the MOP performance for various values of the correlation coefficients ρ_1 and ρ_2. It can be observed that as ρ_2 approaches unity, there is no substantial performance gain as opposed to when ρ_1 tends to unity. Hence, it can be implied that for relay selection with perfect CSI in the D2D communication, the mutual cooperation between the D2D and cellular networks become more beneficial to both systems regardless of the nature of the CSI used for the second relay selection strategy. Fig. 2 illustrates the analytical MOP performance as a function of the number of relays N with varied L and ρ_1. As can be seen, for a fixed ρ_1, i.e., $\rho_1 \in \{0.1, 0.9, 1\}$, the MOP improves as L decreases. This implies that a large number of CUs can have a detrimental effect on the mutual cooperation between the D2D communication and cellular network. This is due to the fact that all the CUs interfere with the D2D communication at the DR and therefore, the impact of interference is substantial. Moreover, we note that the performance gap between $L = 4$ and $L = 10$ greatly increases as ρ_1 improves. Furthermore, there is an error floor in all cases as N becomes fairly large. It can be inferred that a very populated D2D communication in terms of relays, does not further benefit the two networks.

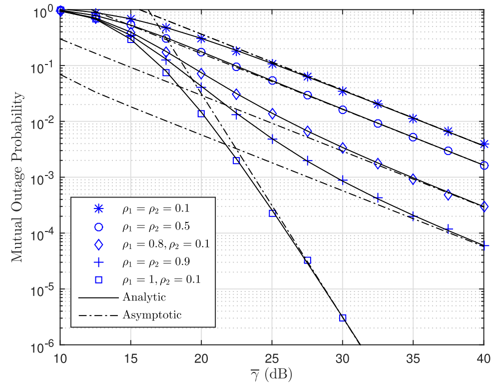

Fig. 1. MOP versus $\bar{\gamma}$ for $L = N = 4$ and different ρ_1 and ρ_2.

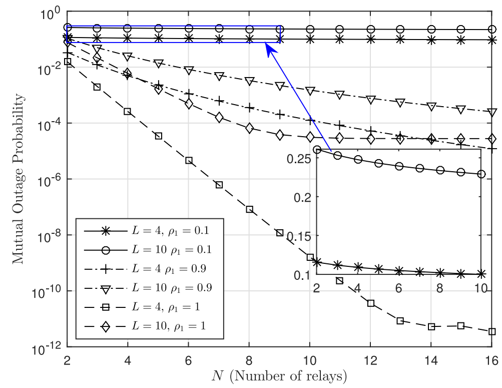

Fig. 2. MOP versus N for $\bar{\gamma} = 25$ dB, $\rho_2 = 0.1$, and various ρ_1.

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