maximum value until $Q = 40$ in the proposed SGRA-NORA scheme. It indicates that depending on a given number of RBs for M2M communications, the eNodeB can optimally allocate RBs to u and v in order to achieve the maximum RA success probability based on the proposed SGRA-NORA. However, in the conventional RA scheme, it requires a larger number of PRACHs ($u = 4$) and RA-S3CHs ($v = 16$), which requires total 56 RBs, in order to achieve a RA success probability over 70%. To achieve an RA success probability of approximately 80%, 22 and 66 RBs are required in the proposed SGRA-NORA scheme and the conventional RA scheme, respectively, which implies that the proposed SGRA-NORA scheme utilizes approximately one-third of radio resources to achieve the same performance, compared with that of the conventional RA scheme.

V. Conclusion

In this paper, we proposed a NORA scheme combined with the SGRA mechanism in order to solve a PUSCH shortage problem in the RA procedure. Since the proposed SGRA-NORA scheme can provide a sufficiently large number of PAs at the first step of RA procedure and can effectively allocate the same RBs to a subgroup of machine nodes belonging to distinct SGs at the second step of RA procedure, it significantly increases both the successful PA transmission and RA-step 3 channel allocation probabilities, which results in the significantly high RA success probability. The simulation result shows that in case of a massive number of RA attempts (50 000 machine nodes, two RA attempts/minute/node), the proposed SGRA-NORA scheme can achieve an RA success probability of approximately 90% with 30 RBs, which is significantly higher than 30% of the conventional RA scheme. As a result, the proposed SGRA-NORA scheme can accommodate a significantly large number of RA requests even with a small number of PUSCH resources reserved for cellular M2M communications.

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On the Spectral Efficiency of Selective Decode-and-Forward Relaying

Hamza Umit Sokun, *Student Member, IEEE*, and Halim Yanikomeroglu, *Member, IEEE*

***Abstract*—Multirelay cooperative relaying enables spatial diversity, often at the expense of spectral efficiency. To alleviate the loss in spectral efficiency due to half-duplex relaying and transmission over orthogonal channels, we propose a novel transmission scheme for selective decode-and-forward (DF) networks. In this scheme, we assume that destination may receive signals from transmitting nodes with different modulation levels. Particularly, we obtain a closed-form expression for both end-to-end (E2E) average error probability and spectral efficiency in such a scheme. Subsequently, using these closed-form expressions and average channel statistics, we perform joint optimization of power allocation and modulation level selection to maximize the E2E spectral efficiency while maintaining a target E2E average error probability and a set of transmit power constraints. Simulation results demonstrate that the transmission scheme proposed herein improves the E2E spectral efficiency significantly, in comparison with the conventional adaptive DF transmission scheme.**

***Index Terms*—Adaptive modulation, cooperative diversity, selective relaying.**

I. Introduction

Cooperative communication has been recognized as an important enabling technology in wireless networks. This technology has been already deployed in the Third-Generation Partnership Project (3GPP) local thermal equilibrium-advanced standards, and more sophisticated cooperative communication techniques are also expected to be adopted in Fifth-Generation (5G) standards [1].

The use of relay-based cooperative transmission brings important benefits, such as effectively extended coverage, and improved link reliability. Despite those benefits, cooperative communication suffers from the loss in spectral efficiency due to half-duplex transmission constraints on relays, and the need of orthogonal time/frequency slots to transmit messages. To mitigate the loss in spectral efficiency, an effective technique, so-called best-relay selection, is proposed, in which only one relay is selected to retransmit the source message [2]. To further improve spectral efficiency, adaptive modulation technique can be used along with the best-relay selection, see [3]–[6] and references therein. In this technique, spectral efficiency is enhanced by changing modulation level adaptively according to channel conditions. It is worth to note that because in amplify-and-forward relaying, the relays simply

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The authors are with the Department of Systems and Computer Engineering, Carleton University, Ottawa, ON K1S 5B6, Canada (e-mail: husokun@sce.carleton.ca; halim@sce.carleton.ca).

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amplify the received signal, and then retransmit to the destination, adaptive modulation technique can be only applied to the source [7].

In this paper, we present a novel transmission scheme for a multirelay selective decode-and-forward (DF) relaying system, in which the destination selects the best relay among a set of candidate relays with different modulation levels. In comparison with the available schemes,[1] the one presented herein is the first to attempt designing modulation level selection and power allocation jointly by using average signal-to-noise ratios (SNRs) when the transmitting nodes have the flexibility to employ different modulation levels. Specifically, in the considered system, we first derive closed-form expressions for the end-to-end (E2E) average error probability as well as spectral efficiency. Then, using the derived close-form expressions and average channel statistics, we jointly optimize power allocation and modulation level selection to maximize the E2E spectral efficiency while satisfying a predetermined E2E average error probability, as well as total and individual transmission power constraints. Since the formulated optimization problem is nonlinear nonconvex and cannot be solved analytically, to implement this optimization problem, we utilize MATLAB command *fmincon* with interior-point method. Finally, numerical results are presented to illustrate the achievable performance gains using the proposed scheme.

II. System and Channel Models

We consider a dual-hop network transmitting information from a source (S) to a destination (D) through L relays ($R_1, \ldots, R_l, \ldots, R_L$), where a direct link does not exist between S and D owing to heavy blockage and long distance transmission.[2] Each node is equipped with a single antenna, and operates in the half-duplex mode in which they can either receive or transmit.[3] The circularly symmetric complex Gaussian channel gains between S and R_i, and between R_i and D are $h_i \sim \mathcal{N}(0, \Omega_{h_i})$ and $f_i \sim \mathcal{N}(0, \Omega_{f_i})$, respectively. These gains are constant over a transmission block, and yet they are independent from one block to another.

In the first time slot, S transmits a data packet using M_S-quadrature amplitude modulation (QAM). Since the packet consists of N-bits, the number of transmitted symbols is $N_S = N/k_S$, where $k_S = \log_2(M_S)$ is the number of bits per symbol (bps). Thus, the packet received at the relay R_l can be written as

$$y_{R_l,i} = \sqrt{P_S} h_l x_i + n_{R_l,i},\ i = 1, \ldots, N_S,\ l = 1, \ldots, L, \quad (1)$$

where P_S is the transmit power from S and n_{R_i} is the circularly symmetric complex additive white Gaussian noise (AWGN) with zero mean and variance N_0. Then, all relays listen to the transmitted packet by the source, and only the relays which decode the packet correctly can contribute in the packet relaying in the second time slot.[4] We denote by $\mathcal{C}$ and $|\mathcal{C}|$, the set of relays that correctly detect the source signal and cardinality of $\mathcal{C}$, respectively. In the second time slot, the best relay R_j is selected to retransmit the packet based on a given relay selection policy, using M_{R_j}-QAM. The number of transmitted symbols in the second time slot is $N_{R_j} = N/k_{R_j}$, where $k_{R_j} = \log_2(M_{R_j})$ bps. The received packet at D from the best relay R_j can be given as

$$y_{D,i} = \sqrt{P_R} f_j x_i + n_{D,i},\ i = 1, \ldots, N_{R_j}, \quad (2)$$

where P_R is the transmit power used in the second time slot, and n_D is the AWGN at D. The resultant instantaneous and average SNRs at the relay R_j in the first time slot can be given as $\gamma_{SR_j} = P_S|h_j|^2/N_0$, and $\overline{\gamma}_{SR_j} = P_S\Omega_{h_j}/N_0$, respectively. The instantaneous and average SNRs at D in the second time slot are $\gamma_{R_jD} = P_S|f_j|^2/N_0$ and $\overline{\gamma}_{R_jD} = P_R\Omega_{f_j}/N_0$, respectively.

Even though the best-relay selection policy based on maximizing the received SNRs works well with the conventional assumption of the same modulation levels at all nodes, it falls short to account for scenarios when the transmitting nodes have different modulation levels. This is due to the fact that different modulation levels have different error resilience properties. Hence, here we choose the best relay in a way to minimize the received bit-error-rate (BER)[5]

$$\text{select jth relay, where } j = \arg\min_{j \in \mathcal{C}} \mathsf{P}_{\text{inst}}^{R_j}(\mathsf{e}),$$

where, for Gray-coded square coherent M_R-QAM over a Rayleigh fading channel, the instantaneous BER at destination can be written as [8]

$$\mathsf{P}_{\text{inst}}^{\text{coop}}(\mathsf{e}|\mathcal{C}) = \mathsf{P}_{\text{inst}}^{\mathsf{R}^*}(\mathsf{e}) \approx \alpha_{R^*} Q\left(\sqrt{2\beta_{R^*}\gamma_{R^*D}}\right)$$

$$\text{with } (\alpha_j, \beta_j) = \begin{cases} (1,1), & M_j = 2 \\ \left(\frac{2-2\Big/\sqrt{M_j}}{\log_2\sqrt{M_j}}, \frac{3}{2(M_j-1)}\right), & M_j \geq 4, \end{cases} \quad (3)$$

where $\mathsf{P}^{\text{coop}}(\mathsf{e}|\mathcal{C})$ denotes the instantaneous BER in the cooperative case when the relays in the set of $\mathcal{C}$ decode correctly, $\mathsf{P}_{\text{inst}}^{\mathsf{R}^*}(\mathsf{e})$ is the instantaneous BER between the selected relay R^*, and the destination. It is worth to mention that $\mathsf{P}_{\text{inst}}^{\text{coop}}(\mathsf{e}|\mathcal{C})$ is a piecewise function with intervals that are dependent on the instantaneous SNRs, and it cannot be expressed solely as a function of the output SNR, i.e., (α, β) may also change depending on the selection. Therefore, there is no straightforward expression for the probability density function (PDF) of the output SNR [9].

III. Performance Analysis

For the discussed system model, here we derive the E2E average error probability and spectral efficiency.

A. Special Case: Two Relays ($L = 2$)

1) E2E Average Error Probability: The E2E average error probability is equal to the average of the error probabilities over

[1]The vast majority of adaptive-modulation schemes use instantaneous SNRs and assign the same modulation level to all nodes. However, in a realistic scenario, transmitting nodes may employ different modulation levels due to having different channel conditions. In addition, using instantaneous SNR can give rise to an excessive signaling overhead. Furthermore, in some cases, instantaneous SNR estimation accuracy can be practically limited.

[2]We consider the use of the relay technology for coverage limited scenarios. Since, in such scenarios, the channel quality of direct link is assumed to be weak, and the discrepancy between the direct and the indirect links is high, there will be a low or no diversity gain utilization.

[3]There is a mounting interest in full-duplex systems in the literature. However, full-duplex systems result in a substantially increased level of complexity. Hence, in this paper, we focus on half-duplex systems.

[4]In practice, a large cyclic redundancy check code can be used for error detection in order to guarantee that the probability of occurrence of undetectable errors is sufficiently small.

[5]There is an inversely proportional relation between SNR and BER. However, the type of modulation also has a direct impact on the performance and, hence, on the variation between SNR and BER. Therefore, when the different modulation levels are employed, the link that has the maximum SNR might not be the most reliable link.

two cases, i.e., cooperative and noncooperative ones, and it can be written as

$$\begin{aligned}\mathsf{P}(\mathsf{e}) &= \Pr\{|\mathcal{C}|=0\}\,\mathsf{P}^{\text{noncoop}}(\mathsf{e}) + \sum_{\ell=1}^{2}\Pr\{|\mathcal{C}|=\ell\}\mathsf{P}^{\text{coop}}(\mathsf{e}|\ell)\\ &= \mathsf{P}^{\text{PEP}}_{\mathsf{SR}_1}(\mathsf{e})\mathsf{P}^{\text{PEP}}_{\mathsf{SR}_2}(\mathsf{e})\mathsf{P}^{\text{noncoop}}(\mathsf{e})\\ &\quad+\left(1-\mathsf{P}^{\text{PEP}}_{\mathsf{SR}_1}(\mathsf{e})\right)\mathsf{P}^{\text{PEP}}_{\mathsf{SR}_2}(\mathsf{e})\mathsf{P}^{\text{coop}}(\mathsf{e}|\mathcal{C}=\{R_1\})\\ &\quad+\left(1-\mathsf{P}^{\text{PEP}}_{\mathsf{SR}_2}(\mathsf{e})\right)\mathsf{P}^{\text{PEP}}_{SR_1}(\mathsf{e})\mathsf{P}^{\text{coop}}(\mathsf{e}|\mathcal{C}=\{R_2\})\\ &\quad+\left(1-\mathsf{P}^{\text{PEP}}_{\mathsf{SR}_1}(\mathsf{e})\right)\left(1-\mathsf{P}^{\text{PEP}}_{\mathsf{SR}_2}(\mathsf{e})\right)\mathsf{P}^{\text{coop}}(\mathsf{e}|\mathcal{C}=\{R_1,R_2\}),\end{aligned}\tag{4}$$

where $\mathsf{P}^{\text{PEP}}_{\mathsf{SR}_i}(\mathsf{e})$ is the average packet error probability (PEP) at the ith relay $i\in\{1,2\}$ when the whole packet is received incorrectly, $\mathsf{P}^{\text{non-coop}}(\mathsf{e})$ and $\mathsf{P}^{\text{coop}}(\mathsf{e}|\mathcal{C})$ denote the average BER in the noncooperative and cooperative cases, respectively.

To find the expressions of $\mathsf{P}^{\text{PEP}}_{\mathsf{SR}_i}(\mathsf{e})$, we follow a reasoning similar to the one given in [10]. Then, $\mathsf{P}^{\text{PEP}}_{\mathsf{SR}_i}(\mathsf{e})$ can be obtained as follows:

$$\mathsf{P}^{\text{PEP}}_{\mathsf{SR}_i}(\mathsf{e}) \approx \sum_{w=1}^{N_S}\sum_{z=0}^{w}\binom{N_S}{w}\binom{w}{z} \times \frac{(-1)^{(w+1)}(k_S\alpha_S)^w A_1^{w-z}A_2^z}{1+2\beta_S(a_1(w-z)+a_2 z)\overline{\gamma}_{SR_i}},\tag{5}$$

where $N_S=N/k_S$, $A_1=0.204$, $A_2=0.147$, $a_1=0.971$, and $a_2=0.525$.

When only one relay is active, i.e., $|\mathcal{C}|=1$, the average BER in the cooperative case $\mathsf{P}^{\text{coop}}(\mathsf{e}|\mathcal{C}=\{R_i\}), i\in\{1,2\}$ in a Rayleigh fading channel can be derived as

$$\begin{aligned}&\mathsf{P}^{\text{coop}}(\mathsf{e}|\mathcal{C}=\{R_i\})\\ &= \int_0^\infty \alpha_i Q(\sqrt{2\beta_i\gamma_{R_iD}})\frac{1}{\overline{\gamma}_{R_iD}}e^{-\frac{\gamma_{R_iD}}{\overline{\gamma}_{R_iD}}}\,d_{\gamma_{R_iD}}\\ &= I(\alpha_{R_i},\beta_{R_i},\overline{\gamma}_{R_iD}),\end{aligned}\tag{6}$$

where $I(a,b,c)=0.5a\left(1-\sqrt{\frac{bc}{1+bc}}\right)$.

When the number of active relays is two, i.e., $|\mathcal{C}|=2$, the instantaneous BER in the cooperative case can be given as

$$\begin{aligned}&\mathsf{P}^{\text{coop}}_{\text{inst}}(\mathsf{e}|\mathcal{C}=\{R_1,R_2\})\\ &= \begin{cases}\alpha_1 Q(\sqrt{2\beta_1\gamma_{R_1D}}), & \mathsf{P}^{\mathsf{R}_1}_{\text{inst}}(\mathsf{e}) \le \mathsf{P}^{\mathsf{R}_2}_{\text{inst}}(\mathsf{e})\\ \alpha_2 Q(\sqrt{2\beta_2\gamma_{R_2D}}), & \mathsf{P}^{\mathsf{R}_2}_{\text{inst}}(\mathsf{e}) < \mathsf{P}^{\mathsf{R}_1}_{\text{inst}}(\mathsf{e}).\end{cases}\end{aligned}\tag{7}$$

We use the approach given in [9] toward developing the average BER in the cooperative case. The average BER results in [9] are obtained for a scenario where the source communicates to the destination via both a direct and indirect links using a single relay, and then, the destination uses selection combining technique to extract spatial diversity. However, herein, we consider a multirelay scenario without a direct link, where the source communicates to the destination through only the best relay. Hence, the average BER $\mathsf{P}^{\text{coop}}(\mathsf{e}|\mathcal{C}=\{R_1,R_2\})$, when $|\mathcal{C}|=2$ can be obtained as

$$\begin{aligned}&\mathsf{P}^{\text{coop}}(\mathsf{e}|\mathcal{C}=\{R_1,R_2\})\\ &= \int\int_{\rho_1}\alpha_1 Q(\sqrt{2\beta_1\gamma_{R_1D}})\frac{e^{-\left(\frac{\gamma_{R_1D}}{\overline{\gamma}_{R_1D}}+\frac{\gamma_{R_2D}}{\overline{\gamma}_{R_2D}}\right)}}{\overline{\gamma}_{R_1D}\overline{\gamma}_{R_2D}}d_{\gamma_{R_1D}}\,d_{\gamma_{R_2D}}\\ &\quad+\int\int_{\rho_2}\alpha_2 Q(\sqrt{2\beta_2\gamma_{R_2D}})\frac{e^{-\left(\frac{\gamma_{R_1D}}{\overline{\gamma}_{R_1D}}+\frac{\gamma_{R_2D}}{\overline{\gamma}_{R_2D}}\right)}}{\overline{\gamma}_{R_1D}\overline{\gamma}_{R_2D}}d_{\gamma_{R_1D}}\,d_{\gamma_{R_2D}},\end{aligned}\tag{8}$$

where $\rho_1=\{(\gamma_{R_1D},\gamma_{R_2D}) : \mathsf{P}^{\mathsf{R}_1}_{\text{inst}}(\mathsf{e}) \le \mathsf{P}^{\mathsf{R}_2}_{\text{inst}}(\mathsf{e})\}\approx\{(\gamma_{R_1D},\gamma_{R_2D}) : \beta_{R_1}\gamma_{R_1D}\ge\beta_{R_2}\gamma_{R_2D}\}$, and $\rho_2=\{(\gamma_{R_1D},\gamma_{R_2D}) : \mathsf{P}^{\mathsf{R}_2}_{\text{inst}}(\mathsf{e}) < \mathsf{P}^{\mathsf{R}_1}_{\text{inst}}(\mathsf{e})\}\approx\{(\gamma_{R_1D},\gamma_{R_2D}) : \beta_{R_2}\gamma_{R_2D}>\beta_{R_1}\gamma_{R_1D}\}$. Note that for the approximate values of ρ_1 and ρ_2, Chernoff bound on the Q-function is first used, and then the constant terms are dropped. After some mathematical manipulations, $\mathsf{P}^{\text{coop}}(\mathsf{e}|\mathcal{C}=\{R_1,R_2\})$ can be rewritten as

$$\begin{aligned}&\mathsf{P}^{\text{coop}}(\mathsf{e}|\mathcal{C}=\{R_1,R_2\})\\ &= \int_{\gamma_{R_1D}=0}^{\infty}\int_{\gamma_{R_2D}=0}^{w_{12}\gamma_{R_1D}}\alpha_1 Q(\sqrt{2\beta_1\gamma_{R_1D}})\\ &\quad\times\frac{e^{-\left(\frac{\gamma_{R_1D}}{\overline{\gamma}_{R_1D}}+\frac{\gamma_{R_2D}}{\overline{\gamma}_{R_2D}}\right)}}{\overline{\gamma}_{R_1D}\overline{\gamma}_{R_2D}}d_{\gamma_{R_1D}}\,d_{\gamma_{R_2D}}\\ &\quad+\int_{\gamma_{R_2D}=0}^{\infty}\int_{\gamma_{R_1D}=0}^{w_{21}\gamma_{R_2D}}\alpha_2 Q(\sqrt{2\beta_2\gamma_{R_2D}})\\ &\quad\times\frac{e^{-\left(\frac{\gamma_{R_1D}}{\overline{\gamma}_{R_1D}}+\frac{\gamma_{R_2D}}{\overline{\gamma}_{R_2D}}\right)}}{\overline{\gamma}_{R_1D}\overline{\gamma}_{R_2D}}d_{\gamma_{R_1D}}\,d_{\gamma_{R_2D}}\\ &= I(\alpha_{R_1},\beta_{R_1},\overline{\gamma}_{R_1D})+I(\alpha_{R_2},\beta_{R_2},\overline{\gamma}_{R_2D})\\ &\quad-\frac{\overline{\gamma}_{R_1D}\overline{\gamma}_{R_2D}}{\overline{\gamma}_{R_2D}+w_{12}\overline{\gamma}_{R_1D}}I\left(\frac{\alpha_{R_1}}{\overline{\gamma}_{R_1D}},\beta_{R_1},\frac{\overline{\gamma}_{R_1D}\overline{\gamma}_{R_2D}}{\overline{\gamma}_{R_2D}+w_{12}\overline{\gamma}_{R_1D}}\right)\\ &\quad-\frac{\overline{\gamma}_{R_1D}\overline{\gamma}_{R_2D}}{\overline{\gamma}_{R_1D}+w_{21}\overline{\gamma}_{R_2D}}I\left(\frac{\alpha_{R_2}}{\overline{\gamma}_{R_2D}},\beta_{R_2},\frac{\overline{\gamma}_{R_1D}\overline{\gamma}_{R_2D}}{\overline{\gamma}_{R_1D}+w_{21}\overline{\gamma}_{R_2D}}\right),\end{aligned}\tag{9}$$

where $w_{ij}=\beta_{R_i}/\beta_{R_j},\ i,j=1,2$.

By substituting (6) and (9) into (4), the E2E average BER can be rewritten as

$$\begin{aligned}\mathsf{P}(\mathsf{e}) \approx\ & \mathsf{P}^{\text{PEP}}_{\mathsf{SR}_1}(\mathsf{e})\mathsf{P}^{\text{PEP}}_{\mathsf{SR}_2}(\mathsf{e})(1/2)\\ &+(1-\mathsf{P}^{\text{PEP}}_{\mathsf{SR}_1}(\mathsf{e}))\mathsf{P}^{\text{PEP}}_{\mathsf{SR}_2}(\mathsf{e})I(\alpha_{R_1},\beta_{R_1},\overline{\gamma}_{R_1D})\\ &+(1-\mathsf{P}^{\text{PEP}}_{\mathsf{SR}_2}(\mathsf{e}))\mathsf{P}^{\text{PEP}}_{\mathsf{SR}_1}(\mathsf{e})I(\alpha_{R_2},\beta_{R_2},\overline{\gamma}_{R_2D})\\ &+(1-\mathsf{P}^{\text{PEP}}_{\mathsf{SR}_2}(\mathsf{e}))(1-\mathsf{P}^{\text{PEP}}_{\mathsf{SR}_1}(\mathsf{e}))\Bigg(I(\alpha_{R_1},\beta_{R_1},\overline{\gamma}_{R_1D})\\ &-\frac{\overline{\gamma}_{R_1D}\overline{\gamma}_{R_2D}}{\overline{\gamma}_{R_2D}+w_{12}\overline{\gamma}_{R_1D}}I\left(\frac{\alpha_{R_1}}{\overline{\gamma}_{R_1D}},\beta_{R_1},\frac{\overline{\gamma}_{R_1D}\overline{\gamma}_{R_2D}}{\overline{\gamma}_{R_2D}+w_{12}\overline{\gamma}_{R_1D}}\right)\\ &+I(\alpha_{R_2},\beta_{R_2},\overline{\gamma}_{R_2D})\\ &-\frac{\overline{\gamma}_{R_1D}\overline{\gamma}_{R_2D}}{\overline{\gamma}_{R_1D}+w_{21}\overline{\gamma}_{R_2D}}I\left(\frac{\alpha_{R_2}}{\overline{\gamma}_{R_2D}},\beta_{R_2},\frac{\overline{\gamma}_{R_1D}\overline{\gamma}_{R_2D}}{\overline{\gamma}_{R_1D}+w_{21}\overline{\gamma}_{R_2D}}\right)\Bigg),\end{aligned}\tag{10}$$

where the average BER in the noncooperative case is considered to be 0.5 [11], viz., $\mathsf{P}^{\text{noncoop}}(\mathsf{e}) = 0.5$, since we assume that there is no direct link between S and D.[6]

2) E2E Spectral Efficiency: For deriving the E2E spectral efficiency, the common approach is to add data rates in each partitioning region multiplied by the occurrence probability of each region; the occurrence probability of each region is calculated using the PDF of output SNR [3]–[7]. However, this approach does not work when the transmitting nodes have different modulation levels, since we do not have the PDF of the output SNR.

We consider a M-QAM system with fixed packet size and fixed symbol duration which are denoted as N-bits and T_s-secs, respectively. Hence, the length of the duration to transmit an N-bits packet using M-QAM is $T_{\text{total}} = T_s N_M$, where $N_M = N/k_M$ symbols, and $k_M = \log_2(M)$ bps. If we assume that bandwidth is $B \approx 1/T_s$, then the spectral efficiency in a link-to-link transmission can be defined as $\eta^{\text{noncoop}} = N/(BT_{\text{total}}) = k_M$.

Let us first discuss a simple cooperative system with a single relay, where the source and the relay transmit the packet using M_S-QAM and M_R-QAM, respectively. For such a system, the E2E spectral efficiency can be found as $\eta_R^{\text{coop}} = N/(BT_{\text{total}}) = k_S k_R/(k_S + k_R)$, where $T_{\text{total}} = T_{\text{total}}^{\text{slot-1}} + T_{\text{total}}^{\text{slot-2}}$ is total duration, $T_{\text{total}}^{\text{slot-1}} = T_s N/k_S$ and $T_{\text{total}}^{\text{slot-2}} = T_s N/k_R$ are the duration of packet transmission in the first and second slots, respectively.

Let us next discuss a more general scenario with two relays, assuming that relays decode the received packet correctly and transmit the packet using M_{R_1}-QAM and M_{R_2}-QAM while the source employs M_S-QAM. In this case, since only the best relay is chosen to participate in forwarding the received packet, we need to reflect the impact of selection policy. Then, the E2E spectral efficiency can be expressed as follows:

$$\eta_{R_{1,2}}^{\text{coop}} = N/\big(B\big(T_{\text{total}}^{\text{slot-1}} + T_{\text{total}}^{\text{slot-2}}\big)\big) = \left(\frac{1}{k_S} + \frac{\Pr\left(\mathsf{P}_{\text{inst}}^{\mathsf{R}_1}(\mathsf{e}) \le \mathsf{P}_{\text{inst}}^{\mathsf{R}_2}(\mathsf{e})\right)}{k_{R_1}} + \frac{\Pr\big(\mathsf{P}_{\text{inst}}^{\mathsf{R}_2}(\mathsf{e}) < \mathsf{P}_{\text{inst}}^{\mathsf{R}_1}(\mathsf{e})\big)}{k_{R_2}}\right)^{-1}, \tag{11}$$

where the probabilities of choosing the relay R_1 and R_2 are $\Pr(\mathsf{P}_{\text{inst}}^{\mathsf{R}_1}(\mathsf{e}) \le \mathsf{P}_{\text{inst}}^{\mathsf{R}_2}(\mathsf{e}))$ and $\Pr(\mathsf{P}_{\text{inst}}^{\mathsf{R}_2}(\mathsf{e}) < \mathsf{P}_{\text{inst}}^{\mathsf{R}_1}(\mathsf{e}))$, respectively, the duration of packet transmission in the first time slot is $T_{\text{total}}^{\text{slot-1}} = T_s N/k_S$, the average duration of packet transmission in the second time slot over two cases is $T_{\text{total}}^{\text{slot-2}} = \Pr(\mathsf{P}_{\text{inst}}^{\mathsf{R}_1}(\mathsf{e}) \le \mathsf{P}_{\text{inst}}^{\mathsf{R}_2}(\mathsf{e}))T_{R_1}^{\text{slot-2}} + \Pr(\mathsf{P}_{\text{inst}}^{\mathsf{R}_2}(\mathsf{e}) < \mathsf{P}_{\text{inst}}^{\mathsf{R}_1}(\mathsf{e}))T_{R_2}^{\text{slot-2}}$, and $T_{R_\ell}^{\text{slot-2}} = T_s N/k_{R_\ell}$, $\ell = 1, 2$, denotes the duration of packet transmission in the second slot if the ℓth relay is chosen.

We provide an approximation, which is tight at high SNRs, for $\Pr(\mathsf{P}_{\text{inst}}^{\mathsf{R}_1}(\mathsf{e}) \le \mathsf{P}_{\text{inst}}^{\mathsf{R}_2}(\mathsf{e}))$ expressions as

$$\begin{aligned}\Pr\left(\mathsf{P}_{\text{inst}}^{\mathsf{R}_1}(\mathsf{e}) \le \mathsf{P}_{\text{inst}}^{\mathsf{R}_2}(\mathsf{e})\right) &\approx \Pr\left(\beta_{R_1}\gamma_{R_1D} \ge \beta_{R_2}\gamma_{R_2D}\right)\\ &= \int_{\gamma_{R_1D}=0}^{\infty}\int_{\gamma_{R_2D}=0}^{w_{12}\gamma_{R_1D}} \frac{1}{\bar{\gamma}_{R_1D}}\frac{1}{\bar{\gamma}_{R_2D}} e^{-\frac{\gamma_{R_1D}}{\bar{\gamma}_{R_1D}}} e^{-\frac{\gamma_{R_2D}}{\bar{\gamma}_{R_2D}}} d_{\gamma_{R_1D}} d_{\gamma_{R_2D}}\\ &= \frac{w_{12}\bar{\gamma}_{R_1D}}{w_{12}\bar{\gamma}_{R_1D} + \bar{\gamma}_{R_2D}}.\end{aligned} \tag{12}$$

In addition, $\Pr\left(\mathsf{P}_{\text{inst}}^{\mathsf{R}_2}(\mathsf{e}) \le \mathsf{P}_{\text{inst}}^{\mathsf{R}_1}(\mathsf{e})\right)$ can be also given as

$$\Pr\left(\mathsf{P}_{\text{inst}}^{\mathsf{R}_2}(\mathsf{e}) \le \mathsf{P}_{\text{inst}}^{\mathsf{R}_1}(\mathsf{e})\right) = \left(1 - \Pr\left(\mathsf{P}_{\text{inst}}^{\mathsf{R}_1}(\mathsf{e}) \le \mathsf{P}_{\text{inst}}^{\mathsf{R}_2}(\mathsf{e})\right)\right) \approx \frac{\bar{\gamma}_{R_2D}}{w_{12}\bar{\gamma}_{R_1D} + \bar{\gamma}_{R_2D}}. \tag{13}$$

So far, the link between node S and the relays are assumed to be error free. To make the analyses more general, we remove this assumption, and then the E2E spectral efficiency can be found as

$$\begin{aligned}\eta^{\text{E2E}} =\; &\Pr\{|\mathcal{C}| = 0\}\,\eta^{\text{noncoop}} + \sum_{\ell=1}^{2}\Pr\{|\mathcal{C}| = \ell\}\eta_\ell^{\text{coop}}\\ =\; &\left(1 - \mathsf{P}_{\mathsf{SR}_1}^{\text{PEP}}(\mathsf{e})\right)\mathsf{P}_{\mathsf{SR}_2}^{\text{PEP}}(\mathsf{e})\frac{k_S k_{R_1}}{(k_S + k_{R_1})}\\ &+ \left(1 - \mathsf{P}_{\mathsf{SR}_2}^{\text{PEP}}(\mathsf{e})\right)\mathsf{P}_{\mathsf{SR}_1}^{\text{PEP}}(\mathsf{e})\frac{k_S k_{R_2}}{(k_S + k_{R_2})}\\ &+ \left(1 - \mathsf{P}_{\mathsf{SR}_1}^{\text{PEP}}(\mathsf{e})\right)\left(1 - \mathsf{P}_{\mathsf{SR}_2}^{\text{PEP}}(\mathsf{e})\right)\\ &\times \frac{k_S k_{R_1} k_{R_2}(\bar{\gamma}_{R_1D}w_{12} + \bar{\gamma}_{R_2D})}{k_{R_1}\bar{\gamma}_{R_2D}(k_S + k_{R_2}) + k_{R_2}\bar{\gamma}_{R_1D}w_{12}(k_S + k_{R_1})},\end{aligned} \tag{14}$$

where $\mathsf{P}_{SR_i}^{\text{PEP}}(\mathsf{e})$ is given in (5), and η^{noncoop} is assumed to be 0 since no communication occurs between S and D when all relays are inactive, i.e., $|\mathcal{C}| = 0$.

B. General L Relays Case

1) E2E Average Error Probability: For an arbitrary number of relays, the E2E average error probability can be obtained as in (10)

$$\begin{aligned}\mathsf{P}(\mathsf{e}) = &\left(\prod_{r=1}^{L}\mathsf{P}_{\mathsf{SR}_r}^{\text{PEP}}(\mathsf{e})\right)\mathsf{P}^{\text{noncoop}}(\mathsf{e})\\ &+ \sum_{r=1}^{L}\sum_{m=1}^{|P_r(\mathcal{S}_{\text{all}})|}\left[\left(\prod_{\kappa_i \in P_{r,m}(\mathcal{S}_{\text{all}})}\left(1 - \mathsf{P}_{SR_{\kappa_i}}^{\text{PEP}}(\mathsf{e})\right)\right)\right.\\ &\left.\times\left(\prod_{\kappa_o \notin P_{r,m}(\mathcal{S}_{\text{all}})}\mathsf{P}_{SR_{\kappa_o}}^{\text{PEP}}(\mathsf{e})\right)\mathsf{P}^{\text{coop}}(\mathsf{e}|\mathcal{C} = P_{r,m}(\mathcal{S}_{\text{all}}))\right],\end{aligned} \tag{15}$$

where S_{all} is the set of all relays' indexes, i.e., $S_{\text{all}} = \{1, \ldots, L\}$, $P_r(S_{\text{all}})$ is the rth element power set of S_{all}, $|P_r(S_{\text{all}})|$ represents the cardinality of $P_r(S_{\text{all}})$, and $P_{r,m}(S_{\text{all}})$ is the mth element of $P_r(S_{\text{all}})$, i.e., $P_r(\mathcal{S}_{\text{all}}) = \left\{P_{r,1}(\mathcal{S}_{\text{all}}), P_{r,2}(\mathcal{S}_{\text{all}}), \ldots, P_{r,|P_r(\mathcal{S}_{\text{all}})|}(\mathcal{S}_{\text{all}})\right\}$.

2) E2E Spectral Efficiency: The framework given for $L = 2$ case can be extended to scenarios with any number of relays for the computation of the E2E spectral efficiency[7]

$$\eta^{\text{E2E}} = \sum_{r=1}^{L}\sum_{m=1}^{|P_r(\mathcal{S}_{\text{all}})|}\left(\prod_{\kappa_i \in P_{r,m}(\mathcal{S}_{\text{all}})}\left(1 - \mathsf{P}_{\mathsf{SR}_{\kappa_i}}^{\text{PEP}}(\mathsf{e})\right)\right)\times\left(\prod_{\kappa_o \notin P_{r,m}(\mathcal{S}_{\text{all}})}\mathsf{P}_{\mathsf{SR}_{\kappa_o}}^{\text{PEP}}(\mathsf{e})\right)\eta_{P_{r,m}(\mathcal{S}_{\text{all}})}^{\text{coop}}. \tag{16}$$

[6]The outcome of transmission over such channel acts as a matter of pure chance, similar to tossing a coin.

[7]Note that as $P_{r,m}(\mathcal{S}_{\text{all}})$ changes, $\eta_{P_{r,m}(\mathcal{S}_{\text{all}})}^{\text{coop}}$ changes as well. For instance, when $|\mathcal{C}| = 3$, $\eta_{R_{1,2,3}}^{\text{coop}} = \big(\frac{1}{k_S} + \frac{\Pr(1 = \arg\min_{i\in\{1,2,3\}}\mathsf{P}_{\text{inst}}^{\mathsf{R}_i}(\mathsf{e}))}{k_{R_1}} + \frac{\Pr(2 = \arg\min_{i\in\{1,2,3\}}\mathsf{P}_{\text{inst}}^{\mathsf{R}_i}(\mathsf{e}))}{k_{R_2}} + \frac{\Pr(3 = \arg\min_{i\in\{1,2,3\}}\mathsf{P}_{\text{inst}}^{\mathsf{R}_i}(\mathsf{e}))}{k_{R_3}}\big)^{-1}$.

IV. Joint Optimization of Power Allocation and Modulation Level Selection

We develop a framework to jointly optimize the transmission powers and the modulation levels to maximize the E2E spectral efficiency while meeting the given requirements on the transmission powers and the E2E average BER. In a somewhat similar context, the modulation level selection problem is studied in [12] using a different approach. Particularly, we consider maximizing the E2E spectral efficiency using the average SNRs under power constraints, whereas in [12], the design objective is to find the best transmission route with the highest spectral efficiency using the instantaneous SNR irrespective of the transmission powers. It is worth noting that our proposed scheme requires less signaling overhead since it relies on average channel statistics.[8]

A. System Constraints

To guarantee a certain level of transmission reliability in the system, the E2E average BER is constrained by a predefined threshold, $\mathsf{P}_{th}(\mathsf{e})$. The nodes have their own individual power constraints, i.e., $P_S \leq P^i_{\max}, i \in \{S, R\}$. Since the interference effect is ignored, the transmitting nodes are inclined to transmit data packets with the maximum power available not only to reduce the E2E average BER but to improve the spectral efficiency as well. Hence, to make the scenario more practical, the total power consumption over two time slots is constrained as $P_S + P_R \leq P_T$.

B. Problem Formulation

The problem is formulated based on the described system constraints, as shown in the following:[9]

$$\max_{M_S, M_{R_i}, P_S, P_R} \quad \eta^{\text{E2E}} \tag{17a}$$

$$\text{subject to} \quad \mathsf{P}(\mathsf{e}) \leq \mathsf{P}_{\text{th}}(\mathsf{e}), \tag{17b}$$

$$P_S + P_R \leq P_T, \tag{17c}$$

$$0 < P_j \leq P^j_{\max},\ j \in \{S, R\}, \tag{17d}$$

$$M_S, M_{R_i} \in \{2, 4, 16, 64, 256\},\ i = 1, \ldots, L. \tag{17e}$$

The optimization problem in (17) is an instance of a non-convex mixed-integer nonlinear program. Since finding an analytical solution for (17) is not possible, we resort to numerical optimization. To that end, we employ MATLAB command *fmincon* with interior-point method.

C. Proposed Algorithm

We propose an algorithm to find the best combination of transmit powers and modulation levels; a pseudocode of the algorithm is given in Algorithm 1. A centralized design is considered to practically implement the algorithm. In such a design, the destination may collect the average SNR values on all links, carry out the optimization task, and spread the obtained solutions to the source and the relays.

Algorithm 1: Joint Optimization of Power Allocation and Modulation Level Selection.

Input: Ω_{h_i}, Ω_{f_i}, P_T, $P^S_{\max}$, $P^R_{\max}$, $\mathsf{P}_{\text{th}}(\mathsf{e})$, $i = 1, \ldots, L$.
Output: M^*_S, $M^*_{R_i}$, P^*_S, P^*_R, $i = 1, \ldots, L$.

Define the set of combinations: Reduce the number of combination of modulation levels, and find $\tilde{\mathcal{S}}_{\mathcal{M}}$.
for $j = 1 : |\tilde{\mathcal{S}}_{\mathcal{M}}|$ **do**
  Power allocation optimization: Find $P^{(j)}_S$, and $P^{(j)}_R$ for the j-th combination $(M^{(j)}_S, M^{(j)}_{R_i}) \in \tilde{\mathcal{S}}_{\mathcal{M}}$.
  Find the E2E spectral efficiency: Using $P^{(j)}_S$, $P^{(j)}_R$, $M^{(j)}_S$ and $M^{(j)}_{R_i}$, obtain $\eta^{\text{E2E}(j)}$ and record all values.
Determine the best combination: Find the best combination with the highest $\eta^{\text{E2E}(j)}$ and assign it to $(M^*_S, M^*_{R_i}, P^*_S, P^*_R)$.

The set of all possible combinations of the modulation levels is denoted by $\mathcal{S}_{\mathcal{M}}$, $\mathcal{M} = (M_S, M_{R_1}, \ldots, M_{R_L})$. The cardinality of $\mathcal{S}_{\mathcal{M}}$ is represented as $|\mathcal{S}_{\mathcal{M}}|$, e.g., for $L = 2$, $|\mathcal{S}_{\mathcal{M}}| = 5^3$. We note that the number of such combinations can grow prohibitively high. To lower the number of combinations, we impose a condition; the modulation level assigned to a relay should be higher than the modulation levels of the relays with the worst channel power, $\mathbb{E}(|f_i|^2) = \Omega_{f_i}$. Thereby, for $L = 2$, the number of combinations can be reduced to $|\tilde{\mathcal{S}}_{\mathcal{M}}| = 75$, where $\tilde{\mathcal{S}}_{\mathcal{M}}$ is the set of reduced combinations. For L relays case, the cardinality of the set of the reduced combinations is equal to $|\tilde{\mathcal{S}}_{\mathcal{M}}| = (5\,L^4 + 50\,L^3 + 175\,L^2 + 250\,L + 120)/24$. Note that the reduction is more pronounced for higher number of relays, and the number of combinations with the proposed simplification does not grow exponentially by the number of relays. On the other hand, from a deployment point of view, since the optimal number of relays in a cell will not be extremely high due to cost issues, the proposed centralized algorithm can be viewed as a starting point for the development of more practical ones.

V. Numerical Results

We evaluate the performance of the proposed method (PM) through numerical comparisons with conventional adaptive modulation method (CM) which serves as a baseline. Even though CM performs a joint optimization similar to PM, in CM, the nodes are constrained to use the same modulation levels.

A. Simulation Setup

We consider a simple scenario in a single-carrier isolated-cell network setup. We assume that a data packet consists of 96 bits, the threshold on the E2E average BER is $\mathsf{P}_{th}(\mathsf{e}) = 10^{-3}$, the total power available over two time slots is $P_T = 1$, and the individual power limits on source and relay nodes are $P^S_{\max} = 0.8\,P_T$, and $P^R_{\max} = 0.8\,P_T$, respectively.

B. Performance of Proposed Algorithm

We start by illustrating the E2E average BER performance in two-relay and three-relay scenarios for given modulation levels at the transmitting nodes. The obtained analytical results using (15) are compared with Monte Carlo simulations. From Fig. 1, it can be observed that the derived analytical results are in good agreement with the simulation results. Fig. 2 investigates the gain realized by PM compared to CM in a

[8]In our scheme, the modulation level decisions remain the same despite small-scale channel variations; these decisions will only change as the link path loss values change (i.e., due to large-scale channel variations). Making the modulation level decisions based on the average SNR values make the protocol more practical and robust. Hence, in such a scheme, signaling overhead is introduced due to the following factors: 1) to acquire the average SNRs of all the links and 2) to inform the transmitting nodes regarding the outcome of the optimization. This overhead is not expected to be excessive.

[9]Since, in our formulation, average error probability is constrained to be less than a predefined threshold and optimization of power allocation is considered, the relatively rare outage events are accounted for.

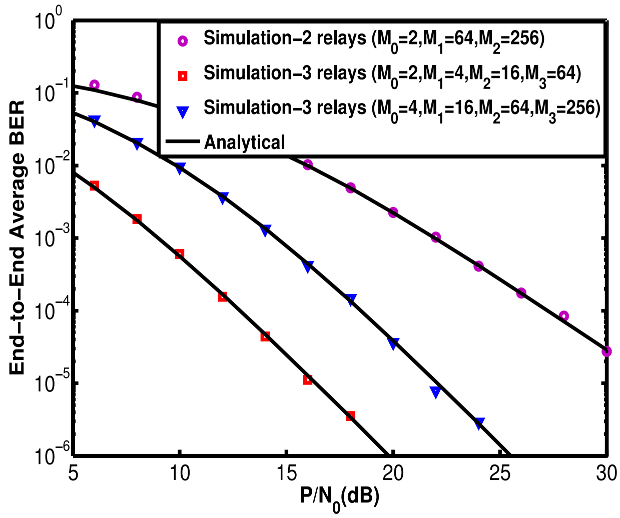

Fig. 1. E2E average BER performance for $L = 2$ in Scenario I ($\Omega_{h_1} = 2\Omega_{h_2} = 2\Omega_{f_1} = \Omega_{f_2}$) and $L = 3$ in Scenario II ($\Omega_{h_1} = 2\Omega_{h_2} = 4\Omega_{h_3} = 4\Omega_{f_1} = 2\Omega_{f_2} = \Omega_{f_3}$), assuming $P_S = P_{R_1} = P_{R_2} = P_{R_3} = P$.

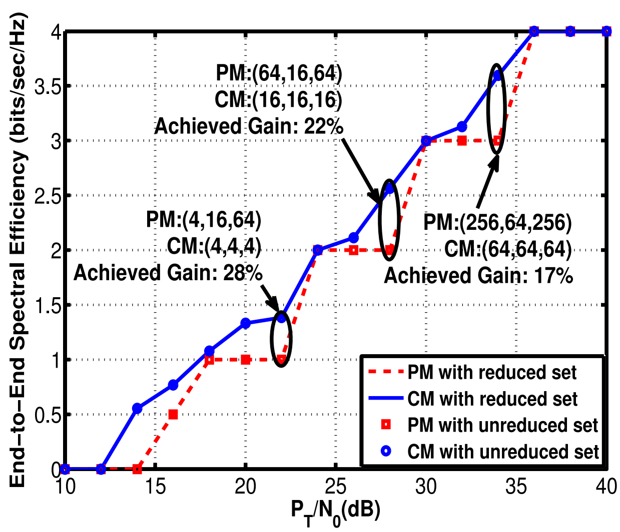

Fig. 2. Gain achieved using PM compared with CM in Scenario I.

two-relay scenario, considering the set of the modulation levels of $\mathcal{M} = \{2, 4, 16, 64, 256\}$, e.g., available modulation formats in the IEEE 802.11ac standard. At some SNR values, we explicitly mention the amount of achieved gain and the set of the modulation levels employed at nodes (M_S, M_{R_1}, M_{R_2}). It is observed that PM outperforms CM over the entire range of SNR values, since PM achieves full utilization of the degrees of freedom in adaptive modulation. Finally, in Fig. 3, the performance of the algorithms are depicted, considering different number of relays in a variety of scenarios and a smaller set of the modulation levels[10] $\mathcal{M} = \{2, 4, 16, 64\}$, e.g., available modulation formats in the IEEE 802.11a standard. PM shows superior performance over CM in all cases, yet the improvement gained with PM can change according to the considered scenario. It is worth noting that an increase in the number of relays helps to improve the E2E spectral efficiency, especially at low SNR values. This is because the E2E average BER gets better as the number of relays increases, and in this way, the threshold on the E2E average BER can be satisfied.

[10]Note that in this case, for L relays, the cardinality of the set of the reduced combinations is equal to $|\tilde{\mathcal{S}}_{\mathcal{M}}| = \frac{2}{3}L^3 + 4L^2 + \frac{22}{3}L + 4$.

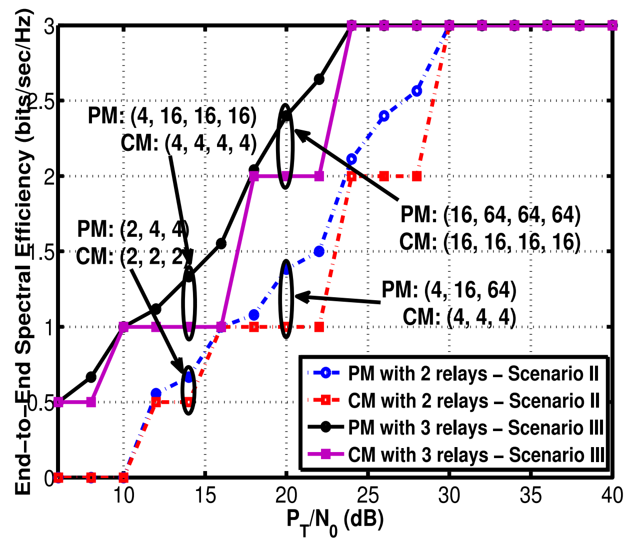

Fig. 3. E2E spectral efficiency for different number of relays in Scenario II and in Scenario III ($2\Omega_{h_1} = \Omega_{h_2} = \Omega_{f_1} = 2\Omega_{f_2}$).

VI. Conclusion

We have discussed a new transmission scheme for selective DF relaying networks, considering the employment of different modulation levels at the transmitting nodes. For this scheme, we have derived both the E2E average error probability and spectral efficiency. Using the derived expressions, we have jointly optimized power allocation and modulation level selection to achieve higher E2E spectral efficiency while meeting a predefined E2E average error probability, and total and individual transmit power constraints. Finally, we have showed the performance of the PM in comparison with the conventional adaptive modulation method.

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Outage Performance Analysis of Full-Duplex Relay-Assisted Device-to-Device Systems in Uplink Cellular Networks

Shuping Dang, *Student Member, IEEE*, Gaojie Chen, *Member, IEEE*, and Justin P. Coon, *Senior Member, IEEE*

***Abstract*—This paper proposes a full-duplex cooperative device-to-device (D2D) communication system, where the relay employed can receive and transmit signals simultaneously. We adopt such a system to assist with D2D transmission. We first derive the conditional cumulative distribution function and the probability density function (pdf) of a series of channel parameters when the interference to the base station is taken into consideration and power control is applied at the D2D transmitter and the relay node. Then, we obtain an exact expression for the outage probability as an integral and as a closed-form expression for a special case, which can be used as a good approximation to the general case when residual self-interference is small. Additionally, we also investigate the power allocation problem between the source and the relay and formulate a suboptimal allocation problem, which we prove to be quasi-concave. Our analysis is verified by the Monte Carlo simulations, and a number of important features of full-duplex cooperative D2D communications can, thereby, be revealed.**

***Index Terms*—Cooperative device-to-device (D2D) communications, full-duplex system, outage performance, power allocation.**

I. Introduction

Underlay device-to-device (D2D) communication coexisting with traditional cellular communication has been a frequent topic of research in both academia and industry for years because of its high power efficiency, high spectral efficiency, and low transmission delay [1]–[3]. Meanwhile, cooperative communication has also gained interest, since it can effectively enhance network reliability and performance [4]. Recently, researchers have tried to combine the merits of both communication systems and have proposed the concept of cooperative D2D communication [5]. However, most recent works treat only the combination of D2D communication with half-duplex relays, which will degrade the system throughput by a fraction due to the use of multiple orthogonal time or frequency slots for one complete transmission. On the other hand, full-duplex relaying is capable of overcoming this shortcoming, but at the cost of producing residual self-interference (SI) [6]. A simplified full-duplex D2D network model is proposed in [7]. The effects of residual SI are analyzed and a numerical optimization of the total transmit power in this full-duplex D2D network model is carried out without presenting analytical results in [8]. Power allocation problems in full-duplex D2D networks are analyzed in [9]. However, all aforementioned works have not considered cooperative relaying between the D2D transmitter and receiver, which restricts the reliability and effectiveness of D2D communication. A cooperative D2D network with a half-duplex relay is analyzed in [10], which exhibits undesirable performance characteristics. A two-pair case in which a transmitter in one pair can assist as a full-duplex relay for the other pair when idle is analyzed in [11]. However, the model considered in that paper is oversimplified and the interference between two pairs is not considered. The most relevant network model related to full-duplex cooperative D2D communication is proposed and analyzed in [12]. However, that paper makes a number of assumptions, e.g., the authors suppose that a relay node is able to transmit the separated signals to two destinations simultaneously by different powers without considering mutual interference. These assumptions can be viewed as impractical in some circumstances.

To provide a comprehensive study of a full-duplex cooperative D2D system, we analyze the outage performance of a novel full-duplex cooperative D2D communication system in which a relay is able to assist the D2D pair only. Our analysis is verified by Monte Carlo simulations. The contributions of this paper can be summarized as follows.

1) We propose a full-duplex relay-assisted D2D communication system, in which power control and the interference from the cellular user equipment (CUE) to the relay and the D2D receiver are considered.
2) We obtain a single integral expression for the end-to-end outage probability of the proposed system, as well as a closed-form approximation to the outage probability when residual SI is small.
3) We formulate a suboptimal power allocation method that is easily implemented due to its quasi-concave nature.

The rest of this paper is organized as follows. In Section II, we present the system model. Then, we analyze the outage performance and power allocation problem of the proposed system in Section III and verify the analysis by simulations in Section IV. Finally, the paper is concluded in Section V.

II. System Model

The model of the proposed full-duplex cooperative D2D system is given in Fig. 1, where one base station (BS), one CUE,[1] one D2D user equipment (DUE) transmitter, one DUE receiver, and one full-duplex relay[2] are considered. They are denoted as B, C, S, D, and R, respectively, and are organized in the set $\Theta = \{B, C, S, D, R\}$. Therefore, $\forall i \neq j$ and $i, j \in \Theta^3$, the channel gain denoted as G_{ij} is

[1]This one-CUE assumption is validated by the scenario in which multiple CUEs are assigned resource blocks in modern cellular systems, and thus we would only expect to receive interference from at most one user in a cell [13].

[2]The full-duplex relay is capable of transmitting and receiving simultaneously, while other nodes are assumed to be half-duplex in this paper.

[3]An exception is given by $i = j = R$, and G_{RR} is employed to denote the instantaneous loop channel gain, leading to residual SI.

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The authors are with the Department of Engineering Science, University of Oxford, Oxford, OX1 3PJ, U.K. (e-mail: shuping.dang@eng.ox.ac.uk; gaojie.chen@eng.ox.ac.uk; justin.coon@eng.ox.ac.uk).

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