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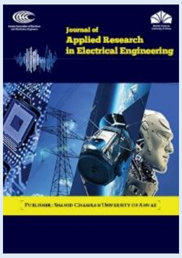

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Research Article

Full-Duplex Device-to-Device Relays in a Novel Hybrid and Adaptive Joint Relaying Network: Symbol Error Analysis and Optimum Power Allocation

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Abstract: This paper proposes a new relaying protocol for transmitting from a cellular user to the base station with the joint cooperation of a Full-Duplex (FD)-enabled Device-to-Device (D2D) pair. In the proposed scheme, the receiver of the D2D acts as a relay, with the cooperation of its transmitter pair via D2D communication between them. The cooperation approach of the D2D receiver is chosen as Adaptive Decode-and-Forward (ADF), while the cooperation strategy of the D2D transmitter is chosen as either ADF, Amplify-and-Forward (AF), or Hybrid relaying protocol. These scenarios are named "Decode and Joint Cooperation," "Amplify and Joint Cooperation," and "Hybrid and Adaptive Joint Cooperation," respectively. The Average Symbol Error Probability (ASEP) of the system is studied over independent and identically distributed (i.i.d) complex Gaussian (Rayleigh envelope) channels, with perfect Channel State Information (CSI) in the presence of Residual Self-Interference (RSI) at the FD relays, as well as Co-Channel Interference (CCI). Moreover, closed-form and high Signal-to-Interference-plus-Noise Ratio (SINR) tight ASEP approximations are established. The optimum power allocation is formulated based on the approximate relations, and the optimal solutions and their characteristics are discussed in detail. Analytical comparisons and simulations confirm the theoretical results and demonstrate significant performance improvements.

Keywords: Cooperative communication, hybrid and adaptive DF/AF protocol, Device-to-Device (D2D) communication, full duplex communication, average symbol error probability, optimal power allocation.

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1. Introduction

The current surge in demand for high-speed and reliable connectivity poses significant challenges to wireless networks [1]. In this context, cooperative communication has emerged as a promising technique in cellular networks. By leveraging the cooperation of one or more relays with cellular users, particularly those situated at the periphery of a cell, the performance parameters of the network can be enhanced [2-5]. The relaying protocols can be categorized into two groups, namely AF and DF [6]. Within the AF relaying protocol, the received signal from a source node is amplified and retransmitted. On the other hand, in the DF approach, a relay node demodulates and decodes the received source signal before transmission. To prevent error propagation and decoding errors, the Adaptive DF (ADF) technique can be employed. In this technique, the relay node switches its operation mode based on certain criteria. Although AF requires low implementation complexity at the relay, it amplifies the noise power. When the quality of the source-relay channel is favourable and the signal can be accurately decoded at the relay node, the Adaptive DF (ADF) approach has been shown to outperform the AF approach [7, 8]. In order to leverage the benefits of both AF and ADF approaches, hybrid protocols, known as Hybrid Adaptive DF (HADF), have been suggested in previous studies [9, 10]. These protocols involve the relay node selecting the most appropriate relaying approach (AF or DF) based on the

Channel State Information (CSI) between the users [11]. Device-to-device (D2D) communication is an emerging technology that presents numerous benefits, including wireless peer-to-peer services and higher spectral efficiency. It is used in various fields, including network traffic offloading, public safety, social services, and applications like gaming and military applications [12]. This paper proposes a new hybrid and adaptive relaying protocol for transmitting data from a cellular user to the base station, utilizing the collaboration of a Full-Duplex (FD)-enabled Device-to-Device (D2D) pair in the context of next-generation wireless networks. The proposed approach involves the D2D receiver acting as a relay, employing an Adaptive-Decode-and-Forward (ADF) relaying approach. The D2D transmitter pairs with the receiver through existing D2D communication, using AF, ADF, or a Hybrid relaying protocol. The selection of the relaying approach is determined based on the D2D transmitter's ability to correctly detect the symbol sent by the cellular user. If successful, the DF approach is used; otherwise, the AF approach is employed. This strategy aims to achieve reliable and efficient information transmission while mitigating the performance degradation of Cellular Users (CUs) caused by D2D users reusing the cellular network's spectrum. Additionally, the use of Full-Duplex (FD) technology improves spectral efficiency, allowing nodes to transmit and receive signals simultaneously over the same frequency in the same time slot. However, it is important to consider the impact of self-interference (SI) on FD communication [15].

The remainder of this paper is organized as follows: Section 2 describes the considered system and presents the physical-layer mathematical framework. In Section 3, we analyze the symbol error probability in the presence of Residual Self-Interference (RSI) and Co-Channel Interference (CCI) in cases where the D2D transmitter cooperates with AF, ADF, or Hybrid relaying protocols, respectively. Due to the complexity of the closed-form formulation, we propose presenting tight approximations with a high Signal-to-Noise Ratio (SNR) to show the asymptotic performance of the systems. Based on this, in Section 4, we formulate the optimal power allocation problem and discuss its solution in cooperative approaches. Furthermore, we compare the efficiency of the hybrid relaying protocol with the case where the D2D transmitter cooperates with either AF or ADF approach. In Section 5, we provide numerical simulations to validate the theoretical findings. Section 6 concludes the paper.

2. System Model and Mathematical Framework

Without loss of generality, in an uplink cellular network with both cellular and D2D communications, we focus on a simple model composed of a base station (D), a cellular user (S) and a pair of D2D users (T, R), as shown in Fig. 1. D2D users are operated in FD and equipped with a transmitting and a receiving antenna. The cellular user sends its information symbols to the base station with the help of D2D pair. We assume that the communication takes place in a Rayleigh flat fading environment, where the channel experiences random fluctuations. However, we assume perfect Channel State Information (CSI) at the receiver nodes, meaning that they have accurate knowledge of the channel conditions. This information helps in optimizing the power allocation and relaying protocols. In our system, each Full-Duplex (FD) node is subject to random Residual Self-Interference (RSI) between its transmit and receive antennas. We model the RSI channels as zero mean circularly symmetric complex Gaussian (ZM-CSCG) random variable [16].

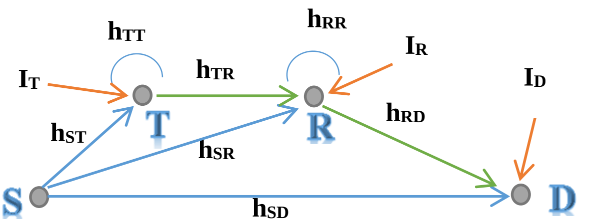


Fig. 1: A simplified model of the proposed hybrid and adaptive cooperative approach.

Moreover, it is assumed that each cellular user can share its uplink channel with a D2D communication in the network, which leads to interference between the D2D link and the cellular uplink. In addition, we fix the total transmitted power P and divide it between users as follows:

$$P_S = \delta_i P \tag{1}$$

$$P_T = \delta_i{}' P \tag{2}$$

$$P_R = (1 - \delta_i - \delta_i{}')P \tag{3}$$

in which the parameters δ_i and $\delta_i{}'$ are power allocation coefficients with $i \in \{AF, ADF, H\}$ which AF, ADF and H refers to the relaying strategy of the D2D transmitter. δ_i and $\delta_i{}'$are in (0,1) interval and satisfy the condition $\delta_i + \delta_i{}' < 1$.

The procedure can be delineated into two distinct phases: the transmission phase and the relaying phase. The destination effectively combines the signal received from the source during Phase 1 with the signal received from the relay during Phase 2. This combination is achieved through the utilization of maximum-ratio combining (MRC) techniques, allowing for the extraction of the transmitted symbols.

During the transmission phase, the cellular user S broadcasts its information to the destination node D with transmission power P_S and the information is also received by D2D receiver R and D2D transmitter T. The received signals at D, R and T are denoted by y_{SD}, y_{SR} and y_{ST}, respectively, and can be written as follows:

$$y_{SD} = \sqrt{P_S} h_{SD} x_S + n_{SD} + I_D \tag{4}$$

$$y_{SR} = \sqrt{P_S} h_{SR} x_S + n_{SR} + I_R + h_{RR} u_R \tag{5}$$

$$y_{ST} = \sqrt{P_S} h_{ST} x_S + n_{ST} + I_T + h_{TT} u_T \tag{6}$$

in which x_S is the transmitted information symbol with unit average energy and belongs to the MQAM constellation with $M = 2^K$. h_{SD}, h_{SR} and h_{ST} are the channel coefficients from the cellular user to the base station, D2D receiver and D2D transmitter and are modelled as ZM-CSCG random variable with variances σ_{SD}^2, σ_{SR}^2 and σ_{ST}^2, respectively. Also, n_{SD}, n_{SR} and n_{ST} are additive white Gaussian noises (AWGN) and are modeled as ZM-CSCG random variable with common variance N_0. Further, I_D, I_R and I_T are CCI terms at D, R and T, respectively and are modelled as ZM-CSCG random variable with variances $\sigma_{I_D}^2$, $\sigma_{I_R}^2$and $\sigma_{I_T}^2$. Moreover, h_{RR} and h_{TT} are the RSI channel coefficients at R and T with variances $\sigma_{h_{RR}}^2$and $\sigma_{h_{TT}}^2$, respectively. Finally, u_R and u_T represent the signals transmitted by R and T to the D and R, respectively.

So we have $P_R = \mathbb{E}\{|u_R(t)|^2\}$ and $P_T = \mathbb{E}\{|u_T(t)|^2\}$. Therefore, the first terms in (4), (5) and (6) represent the desired signals and the others are noise terms because of AWGN, CCI and RSI. The sum of all noise terms are distributed as ZM-CSCG with effective noise power $\sigma^2_{n,SD}$, $\sigma^2_{n,SR}$ and $\sigma^2_{n,ST}$ respectively as follows:

$$\sigma^2_{n,SD} = N_0 + \sigma^2_{I_D} \quad (7)$$

$$\sigma^2_{n,SR} = N_0 + \sigma^2_{I_R} + P_R\sigma^2_{h_{RR}} \quad (8)$$

$$\sigma^2_{n,ST} = N_0 + \sigma^2_{I_T} + P_T\sigma^2_{h_{TT}} \quad (9)$$

The relaying phase of the proposed approach comprises two cooperation scenarios. In these scenarios, R acts as a relay and leverages the cooperation of its transmitter pair T through existing D2D communication. The selection of the DF or AF approach is based on the ability to accurately detect the symbol transmitted by the cellular user. It is assumed that ideal operation is maintained for analytical tractability. In practice, we may apply an SNR threshold at the relay nodes. If the received SINR is higher than the threshold, then the symbol is correctly decoded with a high probability. Details of threshold optimization at the relay can be found in [17]. In the relaying phase, cooperation occurs based on the algorithm shown in Fig. 2. Based on the cooperation strategy of the D2D transmitter node, three scenarios three scenarios can be imagined as follows:

1) In the first scenario D2D transmitter node cooperates with ADF relaying protocol. We call this scenario "Decode and Joint Cooperation".
2) In the second scenario D2D transmitter node cooperates with AF relaying protocol. We call this scenario "Amplify and Joint Cooperation".
3) In the last scenario D2D transmitter node cooperates with hybrid relaying protocol. We call this scenario "Hybrid and Adaptive Joint Cooperation".

Objective: To transmit data from a source node (cellular user) to a destination node (base station) with the cooperation of a D2D pair

Symbols used in the algorithm:

Cellular user: S
Base station: D
D2D transmitter: T
D2D receiver: R

Begin

Step 1. *User S transmits its data symbols to User D. Due to the broadcast phenomenon, users T and R also receive these data symbols.*

Step 2. *User T cooperates with User R using either the ADF, AF, or Hybrid relaying protocol based on the signal received in Step 1.*

Step 3. *User R cooperates with User S using the ADF relaying protocol based on the signals received in Steps 1 and 2.*

Step 4. *User D performs joint combining of the signal received from the user S in step 1 and that from the relay R in step 3, and extracts the transmitted symbols using maximum-ratio combining (MRC).*

End of algorithm.

Fig. 2: Proposed relaying protocol algorithm.

Next, we focus on studying physical-layer mathematical framework of the relaying phase.

In the relaying phase of the "Decode and Joint Cooperation" scenario, the D2D transmitter T cooperates only if it decodes the transmitted symbol correctly. Therefore, $u_T$in (6) equals$\sqrt{\tilde{P}_T}\tilde{x}_S$, where $\tilde{x}_S$denotes the decoded symbol by user T, and $\tilde{P}_T$denotes the transmitted power. Clearly, $\tilde{P}_T$equals P_T in cooperation mode and is equal zero in non-cooperation mode. Then, the D2D receiver R receives the signal as follows:

$$y_{TR,ADF} = \sqrt{\tilde{P}_T}h_{TR}\tilde{x}_S + n_{TR} + I_R + h_{RR}u_R \quad (10)$$

in which h_{TR} is the channel coefficients from the relay R to the base station and is modelled as ZM-CSCG random variable with variances σ^2_{TR}. Also, n_{TR} is AWGN and is modeled as ZM-CSCG random variable with common variance N_0. Sum of all noise terms in (10) are distributed as ZM-CSCG with effective noise power $\sigma^2_{n,TR}$ as follows:

$$\sigma^2_{n,TR} = N_0 + \sigma^2_{I_R} + P_R\sigma^2_{h_{RR}} \quad (11)$$

In the relaying phase of the “Amplify and Joint Cooperation” scenario, the D2D transmitter T simply amplifies the signal received from the cellular user and retransmits the resulting signal to the D2D receiver R. Therefore, $u_T$in (6) equals $\sqrt{\frac{P_T}{\mathbb{E}\{|y_{ST}|^2\}}}y_{ST}$ and the D2D receiver R receives the signal as follows:

$$y_{TR,AF} = h_{TR}\beta_T y_{ST} + n_{TR} + I_R + h_{RR}u_R \quad (12)$$

Finally, in the relaying phase of the “Hybrid and Adaptive Joint Cooperation” scenario, the D2D transmitter T cooperates with the DF relaying protocol and switches to the AF approach in the case of decoding errors. So we have:

$$y_{TR,H} = \begin{cases} \sqrt{\frac{P_T}{\mathbb{E}\{|y_{ST}|^2\}}}h_{TR}y_{ST} + n_{TR} + I_R + h_{RR}u_R\ ; & AF \\ \sqrt{P_T}h_{TR}x_S + n_{TR} + I_R + h_{RR}u_R\ ; & DF \end{cases} \quad (13)$$

In the relaying phase of all of the mentioned scenarios, the D2D receiver R cooperates with the ADF relaying protocol. Therefore, we have:

$$y^{J,scenario}_{RD} = \sqrt{\tilde{P}_R}h_{RD}\tilde{x}_S + n_{RD} + I_D \quad (14)$$

in which h_{RD} is the channel coefficients from the relay R to the base station and is modelled as ZM-CSCG random variable with variances σ^2_{RD}. Also, n_{RD} is AWGN and is modeled as ZM-CSCG random variable with common variance N_0. Superscript "*scenario*" in $y^{J,scenario}_{RD}$ refers to the cooperation scenario of user T and, as a result, is selected from among the members of the set {ADF, AF, H}. $\tilde{P}_R$ refers to the transmitted power of user R. As a result, $\tilde{P}_R$equals P_R in cooperation mode and is equal zero in non-cooperation mode. With knowledge of the channel coefficients h_{SD}, h_{ST},

h_{SR} and h_{RD}, the destination (base station) extracts the transmitted symbols by jointly combining the received signal y_{SD}in (4) and $y_{RD}^{J,scenario}$in (14) using MRC detector. The instantaneous SINR of the MRC output is:

$$\gamma_D^{J,scenario} = \tilde{\gamma}_{RD}^{J,scenario} + \gamma_{SD} \quad (15)$$

where

$$\gamma_{SD} = \frac{P_S|h_{SD}|^2}{\sigma_{n,SD}^2} \quad (16)$$

$$\tilde{\gamma}_{RD}^{J,ADF} = \tilde{\gamma}_{RD}^{J,AF} = \tilde{\gamma}_{RD}^{J,H} = \tilde{\gamma}_{RD} \quad (17)$$

in which $\tilde{\gamma}_{RD} = \frac{\tilde{P}_R|h_{RD}|^2}{\sigma_{n,RD}^2}$. Also, sum of all noise terms in (14) are distributed as ZM-CSCG with effective noise power $\sigma_{n,RD}^2$ as follows:

$$\sigma_{n,RD}^2 = N_0 + \sigma_{I_D}^2 \quad (18)$$

We also define $\boldsymbol{\gamma_{RD}} = \frac{\boldsymbol{P_R|h_{RD}|^2}}{\boldsymbol{\sigma_{n,RD}^2}}$ which represents the SINR value of the signal received from the relay R if it decoded the transmitted symbol correctly.

3. Symbol Error Analysis

In this section, we analyse the symbol error probability (SEP) performance. We also propose tight average SEP (ASEP) approximations at high SINRs to facilitate asymptotic performance analysis.

3.1. Closed Form Conditional SEP Analysis

We know from [18], if square MQAM signals with the utilization of instantaneous signal-to-noise ratios (SNRs) in the system, it becomes possible to calculate the conditional symbol error probability (SEP) in each transmission. This calculation is performed as follows:

$$SEP_{QAM} = \psi_{QAM}(\gamma) \quad (19)$$

where

$$\psi_{QAM}(\gamma) = 4\mathrm{K}\,\mathrm{Q}\left(\sqrt{b_{QAM}\gamma}\right) - 4\mathrm{K}^2\mathrm{Q}^2\left(\sqrt{b_{QAM}\gamma}\right) \quad (20)$$

in which $K = 1 - \frac{1}{\sqrt{M}}$, $b_{QAM} = \frac{3}{M-1}$ and $Q(u) = \frac{1}{\sqrt{2\pi}}\int_u^\infty exp\left(-{t^2}/{2}\right)dt$ is the Gaussian Q-function [19].

Substituting $\gamma_D^{J,scenario}$ (15) into (20), the conditional SEP can be obtained as $\psi_{QAM}\left(\gamma_D^{J,scenario}\right)$. As stated earlier, relay R cooperates with ADF relaying protocol. Therefore, it operates with power P_R only if it decodes the transmitted symbol correctly. With knowledge of the channel coefficients h_{SR}, h_{ST} and h_{TR}, the D2D receiver R extracts the transmitted symbols by jointly combining the received signal y_{SR} in (5) and y_{TR} in (10), (12), or (13) depending on the cooperation approach of the D2D transmitter T using an MRC detector. The instantaneous SINR of the MRC output is:

$$\gamma_R^{J,scenario} = \gamma_{SR} + \gamma_{TR} \quad (21)$$

in which $\gamma_{SR} = \frac{P_S|h_{SR}|^2}{\sigma_{n,SR}^2}$. We also know that if user T cooperates with the AF approach, then $\gamma_{TR} = \gamma_{TR,AF} = \frac{P_S|h_{ST}|^2 P_T|h_{TR}|^2}{\sigma_{n,TR}^2 P_S|h_{ST}|^2 + \sigma_{n,ST}^2 P_T|h_{TR}|^2 + \sigma_{n,TR}^2\sigma_{n,ST}^2}$. On the other hand in the ADF or hybrid relaying protocol, it should be noted that user T tries to decode the transmitted symbol from the signal y_{ST}, and this is done successfully with a probability of $\psi_{QAM}\left(\gamma_{ST} = \frac{P_S|h_{ST}|^2}{\sigma_{n,ST}^2}\right)$, which leads to $\gamma_{TR} = \frac{P_T|h_{TR}|^2}{\sigma_{n,TR}^2}$. Otherwise, $\gamma_{TR} = 0$ in the ADF approach, and $\gamma_{TR} = \gamma_{TR,AF}$in the hybrid relaying protocol.

By Substituting $\gamma_R^{J,scenario}$ into (20), we can achieve probability of incorrect detection in the relay R as $\psi_{QAM}\left(\gamma_R^{J,scenario}\right)$. Therefore, $\psi_{QAM}\left(\gamma_D^{J,scenario}\right)$ equals to:

$$\begin{aligned}\psi_{QAM}\left(\gamma_D^{J,scenario}\right) &= \psi_{QAM}\left(\gamma_R^{J,scenario}\right)\psi_{QAM}(\gamma_{SD}) \\ &+ \left(1 - \psi_{QAM}\left(\gamma_R^{J,scenario}\right)\right) \times \psi_{QAM}(\gamma_{SD} + \gamma_{RD}) \\ &\cong \psi_{QAM}\left(\gamma_R^{J,scenario}\right)\psi_{QAM}(\gamma_{SD}) + \psi_{QAM}(\gamma_{SD} + \gamma_{RD})\end{aligned} \quad (22)$$

in which $\psi_{QAM}\left(\gamma_R^{J,scenario}\right)$could be ignored compared to 1.

3.2. ASEP Analysis and Tight Approximations

Averaging the conditional SEP in (20) over the instantaneous SINR γ, we obtain the average SEP (ASEP) as follows:

$$\Psi_{QAM}(\gamma) = \mathbb{E}\{\psi_{QAM}(\gamma)\} = F\left(1 + \frac{b_{QAM}}{2\sin^2\theta}\gamma\right) \quad (23)$$

where $\mathbb{E}\{.\}$ is the expectation operator and

$$F(x(\theta)) = \frac{4K}{\pi\sqrt{M}}\int_0^{\pi/2}\frac{1}{x(\theta)}d\theta + \frac{4K^2}{\pi}\int_{\pi/4}^{\pi/2}\frac{1}{x(\theta)}d\theta \quad (24)$$

in which $x(\theta)$ denotes a function with the variable θ. In order to derive the Average Symbol Error Probability (ASEP) formulation in equation (24), we utilized two special properties of the Gaussian Q-function. These properties are as follows for any $u \geq 0$ [18, 20]:

1. $Q(u) = \frac{1}{\pi}\int_0^{\pi/2} exp\left(-\frac{u^2}{2\sin^2\theta}\right)d\theta$
2. $Q^2(u) = \frac{1}{\pi}\int_0^{\pi/4} exp\left(-\frac{u^2}{2\sin^2\theta}\right)d\theta$

Even though the resulting ASEP formulation can be efficiently calculated numerically, it is very complex and it is hard to get insight into the system performance from these. To deal with this complexity, we present an approximation of (23) by replacing $\sin^2\theta$ with 1 in the integrands in (24) as follows which is tight at high SNR values.

$$\Psi_{QAM}(\gamma) \approx \tilde{\Psi}_{QAM}(\gamma) = \frac{M-1}{2M(1+b\bar{\gamma})} \quad (25)$$

in which $b = \frac{b_{QAM}}{2}$ and $\bar{\gamma}$ is the expectation value of γ over the Rayleigh fading coefficient(s). Therefore, averaging the conditional SEPs $\psi_{QAM}(\gamma_{SD})$and $\psi_{QAM}(\gamma_{SD} + \gamma_{RD})$ over the instantaneous SINRs γ_{SD} and γ_{RD}^J, we obtain:

$$\Psi_{QAM}(\gamma_{SD}) \approx \tilde{\Psi}_{QAM}(\gamma_{SD}) = \frac{M-1}{2M(1+b\bar{\gamma}_{SD})} \approx \frac{M-1}{2Mb\bar{\gamma}_{SD}} \quad (26)$$

$$\Psi_{QAM}(\gamma_{SD}+\gamma_{RD}) \approx \widetilde{\Psi}_{QAM}(\gamma_{SD}+\gamma_{RD}) = \frac{M-1}{2M(1+b\bar{\gamma}_{SD})(1+b\bar{\gamma}_{RD})} \approx \frac{M-1}{2Mb^2\bar{\gamma}_{SD}\bar{\gamma}_{RD}} \quad (27)$$

where, $\bar{\gamma}_{SD}$ and $\bar{\gamma}_{RD}$ represent the expectation values of γ_{SD} and γ_{RD} over the Rayleigh fading coefficients. These values are equal to $\frac{P_S\sigma_{SD}^2}{\sigma_{n,SD}^2}$ and $\frac{P_R\sigma_{RD}^2}{\sigma_{n,RD}^2}$, respectively.

If the channel links h_{SR}, h_{ST} and h_{TR} are all available in the cooperative network involving users S, T, and R (i.e., $\sigma_{SR}^2 \neq 0$, $\sigma_{ST}^2 \neq 0$ and $\sigma_{TR}^2 \neq 0$), then it is possible to obtain highly accurate approximations of ASEP through the ADF and AF approaches as follows using a similar technique as used in [22] and provided that the SINR is sufficiently high.

$$\Psi_{QAM}(\gamma_R^{J,ADF}) \approx \widetilde{\Psi}_{QAM}(\gamma_R^{J,ADF}) = \frac{1}{b^2\bar{\gamma}_{SR}}\left(\frac{A^2}{\bar{\gamma}_{ST}}+\frac{B}{\bar{\gamma}_{TR}}\right) \quad (28)$$

$$\Psi_{QAM}(\gamma_R^{J,AF}) \approx \widetilde{\Psi}_{QAM}(\gamma_R^{J,AF}) = \frac{B}{b^2\bar{\gamma}_{SR}}\left(\frac{1}{\bar{\gamma}_{ST}}+\frac{1}{\bar{\gamma}_{TR}}\right) \quad (29)$$

The constants A and B, which are dependent on the constellation size M, can be calculated as follows:

$$A = \frac{4K}{\pi\sqrt{M}}\int_0^{\frac{\pi}{2}} sin^2\theta \ d\theta + \frac{4K^2}{\pi}\int_{\frac{\pi}{4}}^{\frac{\pi}{2}} sin^2\theta \ d\theta = \frac{M-1}{2M} + \frac{K^2}{\pi}$$

$$B = \frac{4K}{\pi\sqrt{M}}\int_0^{\frac{\pi}{2}} sin^4\theta \ d\theta + \frac{4K^2}{\pi}\int_{\frac{\pi}{4}}^{\frac{\pi}{2}} sin^4\theta \ d\theta = \frac{3(M-1)}{8M} + \frac{K^2}{\pi}$$

In addition, $\bar{\gamma}_{SR}$, $\bar{\gamma}_{ST}$ and $\bar{\gamma}_{TR}$ represent the expectation values of γ_{SR}, γ_{ST} and γ_{TR} over the Rayleigh fading coefficients. These values can be calculated as $\frac{P_S\sigma_{SR}^2}{\sigma_{n,SR}^2}$, $\frac{P_S\sigma_{ST}^2}{\sigma_{n,ST}^2}$ and $\frac{P_T\sigma_{TR}^2}{\sigma_{n,TR}^2}$, respectively.

The following theorems provide accurate approximations of ASEP for the proposed joint cooperation approach in various scenarios. These approximations are obtained by averaging the respective SEP formulations for each scenario using (22), and then applying (23) to (29).

Theorem 1: The ASEP of the cooperation system using "Decode and Joint Cooperation" scenario and MQAM modulation can be approximated as:

$$\Psi_{QAM}(\gamma_D^{J,ADF}) = \mathbb{E}\{\psi_{QAM}(\gamma_D^{J,ADF})\} \cong \widetilde{\Psi}_{QAM}(\gamma_D^{J,ADF}) = \frac{M-1}{2Mb^2\bar{\gamma}_{SD}}\left[\frac{1}{b\bar{\gamma}_{SR}}\left(\frac{A^2}{\bar{\gamma}_{ST}}+\frac{B}{\bar{\gamma}_{TR}}\right)+\frac{1}{\bar{\gamma}_{RD}}\right] \quad (30)$$

Proof By averaging relation (22) with $\psi_{QAM}(\gamma_R^{J,scenario})$ for the "Decode and Joint Cooperation" scenario, and then applying (26), (27), and (28), we obtain (30).

Theorem 2: If all of the channel links h_{SD}, h_{SR}, h_{RD}, h_{ST} and h_{TR} are available (i.e., $\sigma_{SD}^2 \neq 0, \sigma_{SR}^2 \neq 0, \sigma_{RD}^2 \neq 0, \sigma_{ST}^2 \neq 0$ and $\sigma_{TR}^2 \neq 0$), then the ASEP of the cooperation system using "Amplify and Joint Cooperation" scenario and MQAM modulation can be tightly approximated as:

$$\Psi_{QAM}(\gamma_D^{J,AF}) = \mathbb{E}\{\psi_{QAM}(\gamma_D^{J,AF})\} \cong \widetilde{\Psi}_{QAM}(\gamma_D^{J,AF}) = \frac{M-1}{2Mb^2\bar{\gamma}_{SD}}\left[\frac{B}{b\bar{\gamma}_{SR}}\left(\frac{1}{\bar{\gamma}_{ST}}+\frac{1}{\bar{\gamma}_{TR}}\right)+\frac{1}{\bar{\gamma}_{RD}}\right] \quad (31)$$

Proof By averaging relation (22) with $\psi_{QAM}(\gamma_R^{J,scenario})$ for the "Amplify and Joint Cooperation" scenario, and then applying (26), (27), and (29), we obtain (31).

Theorem 3: If all of the channel links h_{SD}, h_{SR}, h_{RD}, h_{ST} and h_{TR} are available (i.e., $\sigma_{SD}^2 \neq 0, \sigma_{SR}^2 \neq 0, \sigma_{RD}^2 \neq 0, \sigma_{ST}^2 \neq 0$ and $\sigma_{TR}^2 \neq 0$), then the ASEP of the cooperation system using "Hybrid and Adaptive Joint Cooperation" scenario and MQAM modulation can be tightly approximated as:

$$\Psi_{QAM}(\gamma_D^{J,H}) = \mathbb{E}_\gamma\{\psi_{QAM}(\gamma_D^{J,H})\} \cong \widetilde{\Psi}_{QAM}(\gamma_D^{J,H}) = \frac{M-1}{2Mb^2\bar{\gamma}_{SD}}\left\{\frac{M-1}{2Mb\bar{\gamma}_{SR}}\left[\frac{B}{b\bar{\gamma}_{ST}}\left(\frac{1}{\bar{\gamma}_{ST}}+\frac{1}{\bar{\gamma}_{TR}}\right)+\frac{1}{\bar{\gamma}_{TR}}\right]+\frac{1}{\bar{\gamma}_{RD}}\right\} \quad (32)$$

Proof By averaging (22) with $\psi_{QAM}(\gamma_R^{J,scenario})$ for the "Hybrid and Adaptive Joint Cooperation" scenario, and then applying (26), (27), (28) and (29), we obtain (32).

4. Power Optimization and Performance Comparison

Optimizing the transmitted power to achieve optimal performance levels with the minimum transmitted power is crucial, particularly for fifth-generation (5G) and beyond cellular networks [21]. The findings from the previous section highlight that the ASEP in cooperative approaches is dependent not only on the transmitted power but also on the power allocation method employed. To determine the optimal power allocation for each cooperative approach, we can solve the following optimization problems:

$$(\delta_{scenario}{}^*, \delta'_{scenario}{}^*) = \arg\min_{\delta_{scenario},\delta'_{scenario}} \Psi_{QAM}(\gamma_D^{scenario}) \quad (33)$$

such that

$$0 < \delta_{scenario}, \delta'_{scenario} < 1$$

and

$$0 < \delta_{scenario} + \delta'_{scenario} < 1$$

The exact analytical expressions for ASEP in integral form are not practical for evaluating the proposed power allocation rules. Therefore, we use $\widetilde{\Psi}_{QAM}(\gamma_D^{J,ADF})$, $\widetilde{\Psi}_{QAM}(\gamma_D^{J,AF})$ and $\widetilde{\Psi}_{QAM}(\gamma_D^{J,H})$ instead of $\Psi_{QAM}(\gamma_D^{J,ADF})$, $\Psi_{QAM}(\gamma_D^{J,AF})$ and $\Psi_{QAM}(\gamma_D^{J,H})$ in (33). We then employ (1), (2), and (3) and take the derivative with respect to the power allocation coefficients, setting the resulting derivatives to 0 to obtain the optimal power allocation solutions. So we have:

$$\begin{cases}\dfrac{\partial\widetilde{\Psi}_{QAM}\left(\gamma_D^{J,ADF}\right)}{\partial\delta_{J,ADF}}=0\\ \dfrac{\partial\widetilde{\Psi}_{QAM}\left(\gamma_D^{J,ADF}\right)}{\partial\delta'_{J,ADF}}=0\end{cases}\tag{34}$$

$$\begin{cases}\dfrac{\partial\widetilde{\Psi}_{QAM}\left(\gamma_D^{J,AF}\right)}{\partial\delta_{J,AF}}=0\\ \dfrac{\partial\widetilde{\Psi}_{QAM}\left(\gamma_D^{J,AF}\right)}{\partial\delta'_{J,AF}}=0\end{cases}\tag{35}$$

$$\begin{cases}\dfrac{\partial\widetilde{\Psi}_{QAM}\left(\gamma_D^{J,H}\right)}{\partial\delta_{J,H}}=0\\ \dfrac{\partial\widetilde{\Psi}_{QAM}\left(\gamma_D^{J,H}\right)}{\partial\delta'_{J,H}}=0\end{cases}\tag{36}$$

Since obtaining closed-form solutions for the aforementioned sets of equations is challenging, we rely on numerical methods to determine the optimal power allocation coefficients with high precision. Nonetheless, there exist common special cases that simplify the equation complexities, which are discussed in the following.

Case 1: If we assume a fixed power allocation for the D2D transmitter and neglect the effects of co-channel interference (CCI) and residual self-interference (RSI) components in comparison to the Gaussian noise term, the following results hold:

$$\delta_{J,ADF}=\frac{D_1^{J,ADF}}{\sqrt[3]{D_2^{J,ADF}}}+\sqrt[3]{D_2^{J,ADF}}+D_3^{J,ADF}\tag{37}$$

$$\delta_{J,AF}=\frac{D_1^{J,AF}}{\sqrt[3]{D_2^{J,AF}}}+\sqrt[3]{D_2^{J,AF}}+D_3^{J,AF}\tag{38}$$

$$D_4^{J,H}\delta_{J,H}^4+D_3^{J,H}\delta_{J,H}^3+D_2^{J,H}\delta_{J,H}^2+D_1^{J,H}\delta_{J,H}+D_0^{J,H}=0\tag{39}$$

where $D_1^{J,ADF}$, $D_2^{J,ADF}$, $D_3^{J,ADF}$, $D_1^{J,AF}$, $D_2^{J,AF}$, $D_3^{J,AF}$, $D_0^{J,H}$, $D_1^{J,H}$, $D_2^{J,H}$, $D_3^{J,H}$ and $D_4^{J,H}$ are constants with the following definitions. We also define $\bar{\gamma}$ as $\frac{P}{N_0}$.

$$D_1^{J,ADF}=\frac{\sigma_{RD}^2\left(\frac{-3A^2}{b\bar{\gamma}\sigma_{ST}^2\sigma_{SR}^2}+\left(\delta'_{J,ADF}-1\right)\frac{-2B}{b\bar{\gamma}\sigma_{SR}^2\sigma_{TR}^2\delta'_{J,ADF}}\right)}{6}+\left(\frac{\delta'_{J,ADF}-1-\sigma_{RD}^2\frac{-2B}{b\bar{\gamma}\sigma_{SR}^2\sigma_{TR}^2\delta'_{J,ADF}}}{6}\right)^2$$

$$D_2^{J,ADF}=\left(\left(\left(\left(\frac{\delta'_{J,ADF}-1-\sigma_{RD}^2\frac{-2B}{b\bar{\gamma}\sigma_{SR}^2\sigma_{TR}^2\delta'_{J,ADF}}}{6}\right)^3+\left(\frac{\sigma_{RD}^2\left(\frac{-3A^2}{b\bar{\gamma}\sigma_{ST}^2\sigma_{SR}^2}+\left(\delta'_{J,ADF}-1\right)\frac{-2B}{b\bar{\gamma}\sigma_{SR}^2\sigma_{TR}^2\delta'_{J,ADF}}\right)}{24}\right)\times\left(\frac{\delta'_{J,ADF}-1-\sigma_{RD}^2\frac{-2B}{b\bar{\gamma}\sigma_{SR}^2\sigma_{TR}^2\delta'_{J,ADF}}}{6}\right)+\frac{\frac{-3A^2}{b\bar{\gamma}\sigma_{ST}^2\sigma_{SR}^2}\sigma_{RD}^2\left(\delta'_{J,ADF}-1\right)}{4}\right)^2-\left(D_1^{J,ADF}\right)^3\right)^{0.5}-\left(\frac{\delta'_{J,ADF}-1-\sigma_{RD}^2\frac{-2B}{b\bar{\gamma}\sigma_{SR}^2\sigma_{TR}^2\delta'_{J,ADF}}}{6}\right)^3-\left(\frac{\sigma_{RD}^2\left(\frac{-3A^2}{b\bar{\gamma}\sigma_{ST}^2\sigma_{SR}^2}+\left(\delta'_{J,ADF}-1\right)\frac{-2B}{b\bar{\gamma}\sigma_{SR}^2\sigma_{TR}^2\delta'_{J,ADF}}\right)}{24}\right)\times\left(\frac{\delta'_{J,ADF}-1-\sigma_{RD}^2\frac{-2B}{b\bar{\gamma}\sigma_{SR}^2\sigma_{TR}^2\delta'_{J,ADF}}}{6}\right)+\frac{\frac{-3A^2}{b\bar{\gamma}\sigma_{ST}^2\sigma_{SR}^2}\sigma_{RD}^2\left(\delta'_{J,ADF}-1\right)}{4}$$

$$D_3^{J,ADF}=-\frac{\delta'_{J,ADF}-1-\sigma_{RD}^2\frac{-2B}{b\bar{\gamma}\sigma_{SR}^2\sigma_{TR}^2\delta'_{J,ADF}}}{6}$$

$$D_1^{J,AF}=\frac{\sigma_{RD}^2\left(\frac{-3B}{b\bar{\gamma}\sigma_{ST}^2\sigma_{SR}^2}+\left(\delta'_{J,AF}-1\right)\frac{-2B}{b\bar{\gamma}\sigma_{SR}^2\sigma_{TR}^2\delta'_{J,AF}}\right)}{6}+\left(\frac{\delta'_{J,AF}-1-\sigma_{RD}^2\frac{-2B}{b\bar{\gamma}\sigma_{SR}^2\sigma_{TR}^2\delta'_{J,AF}}}{6}\right)^2$$

$$D_2^{J,AF}=\left(\left(\left(\left(\frac{\delta'_{J,AF}-1-\sigma_{RD}^2\frac{-2B}{b\bar{\gamma}\sigma_{SR}^2\sigma_{TR}^2\delta'_{J,AF}}}{6}\right)^3+\left(\frac{\sigma_{RD}^2\left(\frac{-3B}{b\bar{\gamma}\sigma_{ST}^2\sigma_{SR}^2}+\left(\delta'_{J,AF}-1\right)\frac{-2B}{b\bar{\gamma}\sigma_{SR}^2\sigma_{TR}^2\delta'_{J,AF}}\right)}{24}\right)\times\left(\frac{\delta'_{J,AF}-1-\sigma_{RD}^2\frac{-2B}{b\bar{\gamma}\sigma_{SR}^2\sigma_{TR}^2\delta'_{J,AF}}}{6}\right)+\frac{\frac{-3B}{b\bar{\gamma}\sigma_{ST}^2\sigma_{SR}^2}\sigma_{RD}^2\left(\delta'_{J,AF}-1\right)}{4}\right)^2-\left(D_1^{J,AF}\right)^3\right)^{0.5}-\left(\frac{\delta'_{J,AF}-1-\sigma_{RD}^2\frac{-2B}{b\bar{\gamma}\sigma_{SR}^2\sigma_{TR}^2\delta'_{J,AF}}}{6}\right)^3-\left(\frac{\sigma_{RD}^2\left(\frac{-3B}{b\bar{\gamma}\sigma_{ST}^2\sigma_{SR}^2}+\left(\delta'_{J,AF}-1\right)\frac{-2B}{b\bar{\gamma}\sigma_{SR}^2\sigma_{TR}^2\delta'_{J,AF}}\right)}{24}\right)\times\left(\frac{\delta'_{J,AF}-1-\sigma_{RD}^2\frac{-2B}{b\bar{\gamma}\sigma_{SR}^2\sigma_{TR}^2\delta'_{J,AF}}}{6}\right)+\frac{\frac{-3B}{b\bar{\gamma}\sigma_{ST}^2\sigma_{SR}^2}\sigma_{RD}^2\left(\delta'_{J,AF}-1\right)}{4}$$

$$D_3^{J,AF} = -\frac{\delta'_{J,AF} - 1 - \sigma_{RD}^2 \frac{-2B}{b\bar{\gamma}\sigma_{SR}^2\sigma_{TR}^2\delta'_{J,AF}}}{6}$$

$$D_0^{J,H} = \frac{2B(1-M)\sigma_{RD}^2\left(1-\delta'_{J,H}\right)^2}{Mb^2(\bar{\gamma})^2\sigma_{SR}^2\sigma_{ST}^4}$$

$$D_1^{J,H} = \frac{4B(M-1)\left(1-\delta'_{J,H}\right)\sigma_{RD}^2}{Mb^2\bar{\gamma}\sigma_{SR}^2\sigma_{ST}^4} - \frac{3B(M-1)\left(1-\delta'_{J,H}\right)^2\sigma_{RD}^2}{2Mb^2(\bar{\gamma})^2\delta'_{J,H}\sigma_{SR}^2\sigma_{ST}^2\sigma_{TR}^2}$$

$$D_2^{J,H} = \frac{3B(M-1)\left(1-\delta'_{J,H}\right)\sigma_{RD}^2}{Mb^2(\bar{\gamma})^2\delta'_{J,H}\sigma_{SR}^2\sigma_{ST}^2\sigma_{TR}^2} - \frac{2B(M-1)\sigma_{RD}^2}{Mb^2\bar{\gamma}\sigma_{SR}^2\sigma_{ST}^4} + \frac{(1-M)\left(1-\delta'_{J,H}\right)^2\sigma_{RD}^2}{Mb\delta'_{J,H}\bar{\gamma}\sigma_{SR}^2\sigma_{TR}^2}$$

$$D_3^{J,H} = \frac{2(M-1)\left(1-\delta'_{J,H}\right)\sigma_{RD}^2}{Mb\delta'_{J,H}\bar{\gamma}\sigma_{SR}^2\sigma_{TR}^2} - \frac{3B(M-1)\sigma_{RD}^2}{2Mb^2(\bar{\gamma})^2\delta'_{J,H}\sigma_{SR}^2\sigma_{ST}^2\sigma_{TR}^2} + \delta'_{J,H} - 1$$

$$D_4^{J,H} = \frac{(1-M)\sigma_{RD}^2}{Mb\delta'_{J,H}\bar{\gamma}\sigma_{SR}^2\sigma_{TR}^2} + 2$$

Case 2: If we assume a fixed power allocation for the cellular user and neglect the effects of co-channel interference (CCI) and residual self-interference (RSI) components in comparison to the Gaussian noise term, the following results hold:

$$\delta'_{J,ADF} = \frac{\sqrt{\frac{B\sigma_{RD}^2}{b\delta_{J,ADF}\bar{\gamma}\sigma_{TR}^2\sigma_{SR}^2}}}{1+\sqrt{\frac{B\sigma_{RD}^2}{b\delta_{J,ADF}\bar{\gamma}\sigma_{TR}^2\sigma_{SR}^2}}}\left(1-\delta_{J,ADF}\right) \quad (40)$$

$$\delta'_{J,AF} = \frac{\sqrt{\frac{B\sigma_{RD}^2}{b\delta_{J,AF}\bar{\gamma}\sigma_{TR}^2\sigma_{SR}^2}}}{1+\sqrt{\frac{B\sigma_{RD}^2}{b\delta_{J,AF}\bar{\gamma}\sigma_{TR}^2\sigma_{SR}^2}}}\left(1-\delta_{J,AF}\right) \quad (41)$$

$$\delta'_{J,H} = \frac{\sqrt{\frac{(M-1)\sigma_{RD}^2}{2Mb\bar{\gamma}\delta_{J,H}\sigma_{SR}^2\sigma_{TR}^2}\left[\frac{B}{b\bar{\gamma}\delta_{J,H}\sigma_{ST}^2}+1\right]}}{1+\sqrt{\frac{(M-1)\sigma_{RD}^2}{2Mb\bar{\gamma}\delta_{J,H}\sigma_{SR}^2\sigma_{TR}^2}\left[\frac{B}{b\bar{\gamma}\delta_{J,H}\sigma_{ST}^2}+1\right]}}\left(1-\delta_{J,H}\right) \quad (42)$$

We interpret the results of optimal power allocation as follows:

1. In AF cooperation systems, the power allocation does not depend on the modulation scheme used. This is different from ADF cooperation systems, where the optimal power allocation may vary based on the modulation scheme employed. This is because in the AF approach, the relay amplifies and forwards the received signal to the destination, regardless of the type of signal received. On the other hand, in ADF cooperation systems, the relay forwards information to the destination only if it correctly decodes the received signal. The process of decoding at the relay necessitates the utilization of particular modulation information, leading to the development of a power allocation scheme that is contingent upon the modulation technique employed.
2. The optimal power allocation is independent of the direct link between the cellular user and the base station, and depends solely on the channel links associated with the relay.
3. The optimal power allocated to the cooperator user in each cooperation scenario is lower than the power allocated to the cellular user. If the link quality between the cellular user and cooperator user is significantly worse than that between the cooperator user and the base station, then the power allocated to the cellular user approaches the maximum power level P. When the link quality between the cellular user and cooperator user is poor, it becomes difficult for the cooperator user to correctly decode the transmitted symbol. Thus, its forwarding role is less important, and it makes sense to allocate more power to the source. Conversely, when the link quality between the cellular user and cooperator user is very good, the cooperator user can always decode the transmitted symbol accurately, and we can consider it as a copy of the cellular user and allocate almost equal power to them.
4. In the proposed hybrid and adaptive approach, the relay benefits from the cooperation of user T, resulting in a higher probability of correctly detecting the symbol sent by the cellular user. As a result, based on the explanation in the previous paragraph, solving the power allocation problem in this approach tends to allocate half of the total available power (total power minus the power allocated to user T), more than in the AF and ADF approaches. In the proposed hybrid and adaptive approach, the relay benefits from the cooperation of user T, resulting in a higher probability of correctly detecting the symbol sent by the cellular user. As a result, based on the explanation in the previous paragraph, solving the power allocation problem in this approach tends to allocate half of the total available power (total power minus the power allocated to user T), more than in the AF and ADF approaches.

5. It is worth noting that by increasing the power available to the cellular user, both the desired signal power and power of the RSI component increase simultaneously. Conversely, reducing the transmitted power causes both the desired signal power and power of the RSI component to decrease. Therefore, the best transmission quality from the cellular user to the relay is achieved with intermediate values of transmitted power (neither high nor low). In this condition, and based on the explanations of the previous paragraphs regarding optimal power allocation, the smallest proportion of available power will be assigned to the cellular user.

The superiority of the proposed relaying protocol's performance compared to the ADF and AF approaches is evident from the comparison of their average symbol error probability tight approximations in (28) to (32). We conduct a comparative study on the performance of the proposed relaying protocol, utilizing asymptotically tight ASEP approximations and optimal power allocation solutions. Initially, we compare the average symbol error probability of the "Decode and Joint Cooperation" scenario with that of the "Amplify and Joint Cooperation" scenario, using the parameter $\lambda_{J,AF}^{J,ADF}$, which is defined as follows:

$$\lambda_{J,AF}^{J,ADF} = \frac{\Psi_{QAM}(\gamma_D^{J,ADF})}{\Psi_{QAM}(\gamma_D^{J,AF})} \approx \frac{\widetilde{\Psi}_{QAM}(\gamma_D^{J,ADF})}{\widetilde{\Psi}_{QAM}(\gamma_D^{AF})} = \frac{\frac{1}{b}\left(\frac{A^2}{\bar{\gamma}_{ST}} + \frac{B}{\bar{\gamma}_{TR}}\right)\gamma_{RD,SR}^r + 1}{\frac{B}{b}\left(\frac{1}{\bar{\gamma}_{ST}} + \frac{1}{\bar{\gamma}_{TR}}\right)\gamma_{RD,SR}^r + 1} \quad (43)$$

in which $\gamma_{RD,SR}^r \triangleq \frac{\bar{\gamma}_{RD}}{\bar{\gamma}_{SR}}$.

Continuing on, we will compare the average symbol error probability of the "Hybrid and Adaptive Joint Cooperation" scenario with that of the "Decode and Joint Cooperation" scenario, using the parameter $\lambda_{J,ADF}^{J,H}$, which is defined as follows:

$$\lambda_{J,ADF}^{J,H} = \frac{\Psi_{QAM}(\gamma_D^{J,H})}{\Psi_{QAM}(\gamma_D^{J,ADF})} \approx \frac{\widetilde{\Psi}_{QAM}(\gamma_D^{J,H})}{\widetilde{\Psi}_{QAM}(\gamma_D^{ADF})} = \frac{\frac{M-1}{2M}\left[\frac{B}{b\bar{\gamma}_{ST}}\left(\frac{1}{\bar{\gamma}_{ST}} + \frac{1}{\bar{\gamma}_{TR}}\right) + \frac{1}{\bar{\gamma}_{TR}}\right]\gamma_{RD,SR}^r + 1}{\left(\frac{A^2}{\bar{\gamma}_{ST}} + \frac{B}{\bar{\gamma}_{TR}}\right)\gamma_{RD,SR}^r + 1} \quad (44)$$

We will now discuss the ratios $\lambda_{J,AF}^{J,ADF}$ and $\lambda_{J,ADF}^{J,H}$ for the following cases.

Case 1: If the channel link quality between the cellular user and the D2D receiver is much worse than that between the D2D receiver and the base station (i.e., $\gamma_{RD,SR}^r \gg 1$), then $\lambda_{J,AF}^{J,ADF}$ tends towards the value $\frac{\frac{1}{b}\left(\frac{A^2}{\bar{\gamma}_{ST}}+\frac{B}{\bar{\gamma}_{TR}}\right)}{\frac{B}{b}\left(\frac{1}{\bar{\gamma}_{ST}}+\frac{1}{\bar{\gamma}_{TR}}\right)}$. In this case, if the channel link quality between the cellular user and the D2D transmitter is much worse than that between the D2D transmitter and receiver (i.e., $\bar{\gamma}_{TR} \gg \bar{\gamma}_{ST}$), then $\lambda_{J,AF}^{J,ADF} \to \frac{A^2}{B}$, which depends on the modulation size M. For instance, when M=4, $\lambda_{J,AF}^{J,ADF} \to 1.3214$, while for sufficiently high values of M, $\lambda_{J,AF}^{J,ADF} \to 1.0175>1$. Consequently, in this case, the "Decode and Joint Cooperation" scenario outperforms the "Amplify and Joint Cooperation" scenario, and this superiority decreases with an increase in M. On the other hand, if the channel link quality between the cellular user and the D2D transmitter is much better than that between the D2D transmitter and receiver (i.e., $\bar{\gamma}_{TR} \ll \bar{\gamma}_{ST}$), then $\lambda_{J,AF}^{J,ADF} \to 1$, which implies that, in this case, the performance of the "Decode and Joint Cooperation" scenario is almost the same as that of the "Amplify and Joint Cooperation" scenario. As the ADF cooperation protocol necessitates a decoding process at the relay, we propose the use of the AF approach in this case to reduce the system complexity.

It should be noted that in this case, the parameter $\lambda_{J,ADF}^{J,H}$ tends towards the value $\frac{\frac{M-1}{2M}\left[\frac{B}{b\bar{\gamma}_{ST}}\left(\frac{1}{\bar{\gamma}_{ST}}+\frac{1}{\bar{\gamma}_{TR}}\right)+\frac{1}{\bar{\gamma}_{TR}}\right]}{\left(\frac{A^2}{\bar{\gamma}_{ST}}+\frac{B}{\bar{\gamma}_{TR}}\right)}$, which demonstrates the superiority of the "Hybrid and Adaptive Joint Cooperation" scenario over the "Decode and Joint Cooperation" scenario.

Case 2: If the channel link quality between the cellular user and the D2D receiver is much better than that between the D2D receiver and the base station (i.e., $\gamma_{RD,SR}^r \to 0$), then $\lambda_{J,AF}^{J,ADF}$ and $\lambda_{J,ADF}^{J,H}$ tend towards 1. This implies that in this case, the performance of the aforementioned scenarios is nearly the same.

5. Numerical Simulations and Discussion

To illustrate the aforementioned theoretical analysis, we conducted computer simulations. We utilized the network topology depicted in Fig. 1 for our study. In all simulations, we normalized the transmitted power and the variance of the channel coefficients to the noise power. Additionally, we set $\sigma_{SD}^2 = 1$. The default values of the other parameters are listed in Table 1.

Table 1: Default values of simulation parameters.

Parameter	Default value/N_0
P	20 dB
σ_{SR}^2	10
σ_{RD}^2	10
σ_{ST}^2	20
σ_{TR}^2	100
$\sigma_{I_D}^2, \sigma_{I_R}^2, \sigma_{I_T}^2$	2 dB
$\sigma_{h_{RR}}^2, \sigma_{h_{TT}}^2$	-10 dB
Maximum error of $\delta_{scenario}^*, \delta_{scenario}'^*$	0.01% of transmitted power

First, we perform simulations to compare the exact analytical ASEP curves with the asymptotically tight ASEP approximations of the proposed relaying protocol scenarios. In this simulation, we set the power of the cellular user and the D2D Transmitter User to 50% and 10% of the total transmitted power, respectively. The results shown in Fig. 3 confirm the close correspondence between the exact analytical and approximate ASEPs. Moreover, it can be observed that although these approximations are derived for high SNR values, they also provide good approximations for moderate SNR scenarios. Therefore, they can be used instead of analytical relationships to determine the optimal power allocation, particularly for middle and high values of SNR. Next, we compare the exact analytical ASEP results of the proposed relaying protocol in all scenarios with the non-cooperative approach using different power allocation schemes. The results in Fig. 4 demonstrate that non-optimal power allocation can lead to performance degradation in all scenarios, resulting in ASEP being worse than the non-cooperative approach. The following simulation is dedicated to the optimum power allocation solution graphs in the proposed relaying protocol scenarios. Based on the discussions presented in Section 4, it is claimed that the optimal power allocation, based on solving (33), follows a general rule: the power allocation criterion is the SINR value of the signal received at the relay (D2D receiver) compared to the SINR value of the signal received at the base station by the relay. The higher this criterion, the greater the percentage of the total transmitted power allocated to the relay, which will not exceed half of the total transmitted power. Conversely, the lower this criterion, the greater the percentage of the total transmitted power allocated to the cellular user. This crucial rule will be confirmed in the following simulation. In Fig. 5, the power allocation coefficients are plotted in terms of the total transmitted power. It can be observed that an increase in the total transmitted power results in an increase in the power of the Relay RSI component in addition to increasing the desired signal power in the relay. At the base station, due to the absence of RSI, only the desired signal power increases. Consequently, the quality of the signal received at the relay decreases compared to the quality of the signal received at the base station. Therefore, with an increase in the total transmitted power, a higher percentage of this power is allocated to the cellular user. A similar discussion can be used to justify the power allocation graphs of the D2D transmitter. However, in this case, the power allocation criterion is the SINR value of the signal received at the D2D transmitter compared to the SINR value of the signal received at the D2D receiver by the D2D transmitter.

The simulations presented in Fig. 6 have demonstrated the distinct capability of the "Hybrid and Adaptive Joint Cooperation" scenario to reduce the total transmitted power required at each ASEP level. The results obtained show a significant reduction in the total transmitted power required to guarantee the ASEP levels compared to the AF and ADF approaches. This is precisely the reason why (as illustrated in Fig. 7), among the proposed approach scenarios, the most significant power savings are assigned to "Hybrid and Adaptive Joint Cooperation", followed by "Decode and Joint Cooperation" scenario, and "Amplify and Joint Cooperation" scenario, respectively. It should be noted that this improvement is more pronounced at smaller threshold levels. This is because guaranteeing low levels of error probability necessitates ensuring a high probability of correct detection in the relay, where the role of D2D transmitter cooperation is crucial.

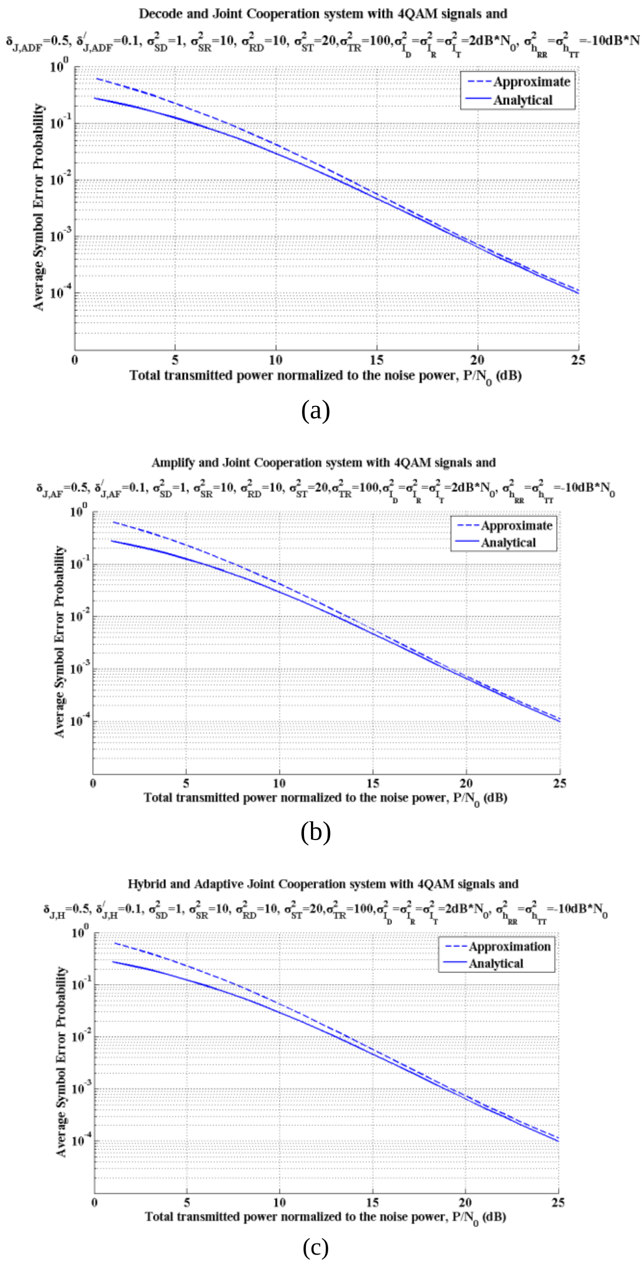
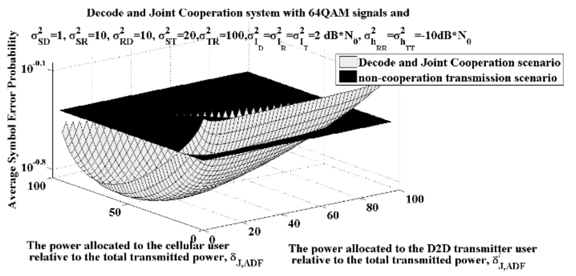


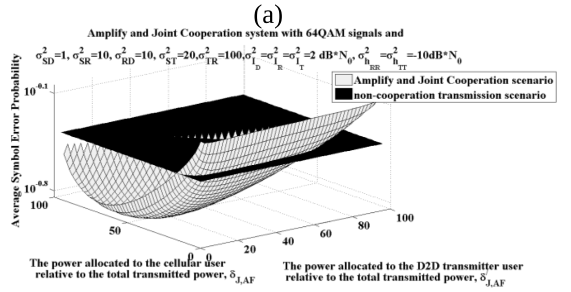
Fig. 3: Comparison of exact analytical and approximate ASEP's in the proposed relaying approach scenarios, (a) decode and oint Cooperation, (b) amplify and Joint Cooperation, (c) hybrid and adaptive joint cooperation.

6. Conclusion

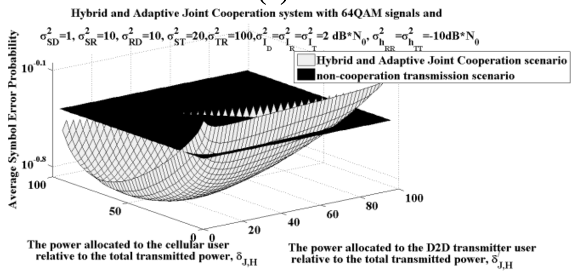
This paper has presented a novel relaying protocol for transmitting from a cellular user to the base station with the joint cooperation of a Full-Duplex (FD)-enabled Device-to-Device (D2D) pair. In the suggested scheme, the recipient of the D2D pair functions as a relay, collaborating with its transmitting counterpart through D2D communication. The



(a)

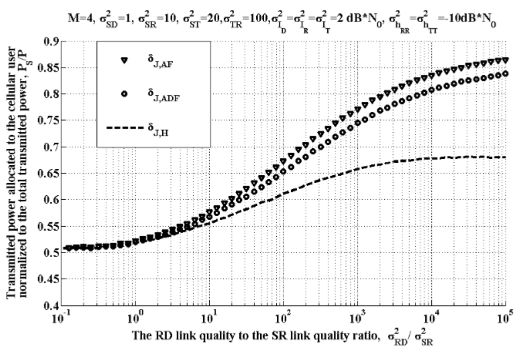


(b)

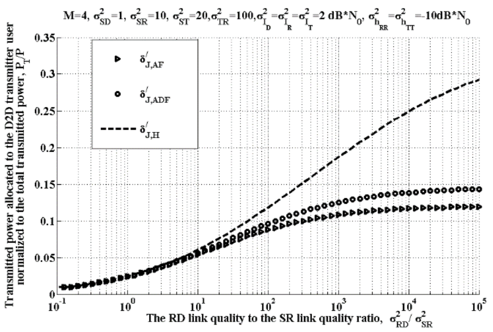


(c)

Fig. 4: Comparison of exact analytical ASEP's in the proposed relaying approach for different power allocation schemes with non-cooperation approach, (a) decode and joint cooperation, (b) amplify and joint cooperation, (c) hybrid and adaptive joint cooperation.



(a)



(b)

Fig. 5: Power allocation coefficients in the proposed relaying approach versus total transmitted power, (a) P_S/P, (b) P_T/P

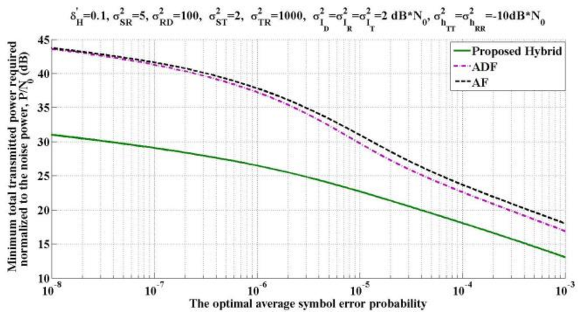
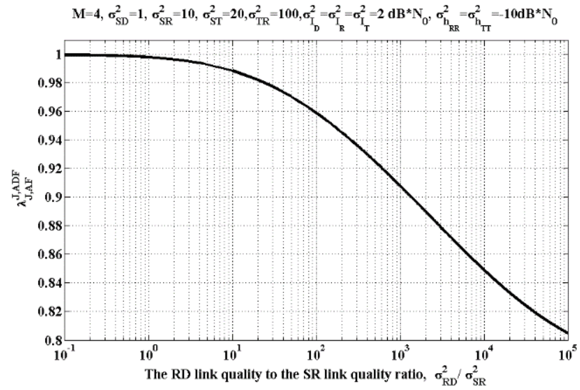
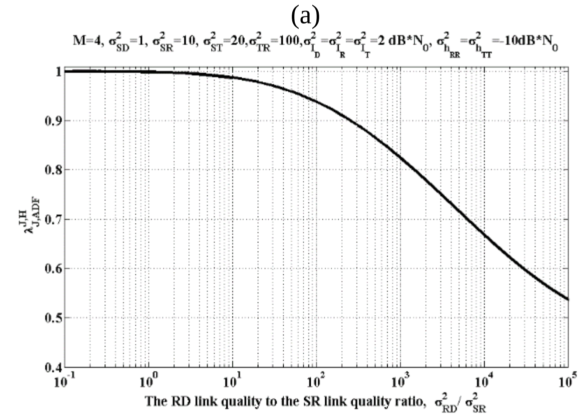


Fig. 6: Minimum total transmitted power required versus ASEP in the relaying approaches.



(a)



(b)

Fig. 7: ASEP comparison of various scenarios of the proposed relaying protocol, (a) $\lambda^{J,ADF}_{J,AF}$, (b) $\lambda^{J,H}_{J,ADF}$.

cooperative strategy employed by the D2D recipient is referred to as Adaptive Decode-and-Forward (ADF), while the cooperative strategy adopted by the D2D transmitter can be either ADF, AF, or a Hybrid relaying protocol. These scenarios are denoted as "Decode and Joint Cooperation," "Amplify and Joint Cooperation," and "Hybrid and Adaptive Joint Cooperation," respectively. The Average Symbol Error Probability (ASEP) of the system has been studied over independent and identically distributed (i.i.d) complex Gaussian (Rayleigh envelope) channels, with perfect Channel State Information (CSI) in the presence of Residual Self-Interference (RSI) at the FD relays, as well as Co-Channel Interference (CCI). Moreover, closed-form and high Signal-to-Interference-plus-Noise Ratio (SINR) tight ASEP approximations have been established. The optimum power allocation has been formulated based on the approximate relations, and the optimal solutions and their characteristics have been discussed in detail. Analytical comparisons and simulations have confirmed the theoretical results and have demonstrated significant performance improvements.

CRediT Authorship Contribution Statement

Mehdi Basiri Abarghouei: Formal analysis, Investigation, Investigation, Software, Roles/Writing - original draft. **Reza Saadat:** Methodology**,** Supervision, Validation, Writing - review & editing

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. The ethical issues; including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, redundancy has been completely observed by the authors.

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