Research Article

Joint Power Control and Relay Selection with Short Packet Communications under Co-channel Interference

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Abstract. *In this paper, a cooperative system where one multiple antenna transmitter communicates with one single antenna receiver with assistance of multiple relay nodes is considered. Under this system setting, with co-channel interference affecting on the relays, we evaluate the system in short packet communication (SPC). Relied on SPC metric, average block error rate (BLER) of the receiver corresponding to given relay is calculated. Next, due to multiple relay, we formulate a problem which joint power allocation and relay selection to minimize the BLER. To address the problem, we divide it into two sub-problems, which are power allocation and relay selection problems. The proposed solution's effectiveness is validated through simulation and analysis results, which demonstrate its superior performance over benchmark methods.*

Keywords

Block error rate, co-channel interference, power control, multiple relay, short packet communication.

1. Introduction

Short packet communication (SPC) has recently emerged as a critical enabler for low-latency in wireless communication networks. By utilizing smaller data packets, SPC enhances the speed and reliability of communications. As a result, it has been increasingly implemented in applications demanding both low latency and high reliability, such as autonomous vehicles, industrial automation, and smart grids, where quick and trustworthy data exchange is crucial. Therefore, SPC have appeared in applications such as: Internet of Things (IoT) systems [1, 2], physical security systems [3], multiple input multiple output systems [4].

Relay communication (RC) can significantly improve the performance of wireless systems, leading to higher data rates and more reliable links. In [5], the authors analysed outage performance for wireless sensor network with energy harvesting. Two methods, half-duplex and full-duplex were implemented in coordinated direct and relay transmission (CDRT) system to evaluate outage probability [6]. In the same CDRT system, with the goal of enhancing spectrum efficiency at the relay, a NOMA stage was introduced, as discussed in [7]. Considering security aspects, [8] investigated the security-reliability trade-off in relay communication (RC) systems, [9] focused on cooperative multi-hop systems, [10] explored wireless sensor networks, and [11] evaluated Unmanned Aerial Vehicle systems. In addition, the integration of energy harvesting into cooperative networks has been extensively investigated to create self-sustaining communication systems [12, 13]. Recently, the outage probability was evaluated in RC system with reconfigurable intelligent surfaces [14] and satellite-terrestrial networks [15].

The relay selection (RS) technique enables the source node to select the optimal relay from a pool of candidates, with the goal of enhancing the system's performance in aspects such as data rate, reliability, energy efficiency, and security. In [16], the authors used two RS approaches including partial and full RS to evaluate the performance of cognitive inter-vehicular relay-assisted system. With the same RS methods introduced in [16], a two-way energy harvesting system with multiple DF relays was investigated in [17] and full-duplex multi-relay networks with energy harvesting in [18]. A machine learning framework was proposed in [19] to predict selected relay for multi-hop system. However, SPC was not considered in these works.

RS in the context of SPC is an open question that previous works have not studied in depth. The authors of [20] proposed two strategies of RS to choose best relay, i.e, a source-driven selection and a relay-driven selection. In the two strategies, optimization of the overall error probability was carried out and compared. The results in this paper showed that the performance obtained from the two strategies is the same. An approach in RS with best relay to obtain trade-off of two key factors such as age of information and energy consumption for a DF relay system was considered in [21]. By optimizing end-to-end signal-to-noise ratio of a cognitive system, an opportunistic RS solution was introduced in [22]. However, joint PA and RS as well as co-channel interference issue has not been investigated in these work. From the above overview, in the first time, we evaluate a multiple relay system in context of SPC where a source chooses a relay based on joint minimum BLER and PA under co-channel interference.

The key contributions are listed as follows:

1. Different from [20, 21, 22], we consider cooperative system where one multiple antenna source conveys information to one destination with assistance of multiple AF relay experienced co-channel interference.

2. Utilizing the beamforming approach, we derive the expressions for the system's average BLER in closed-form and its asymptotic form. We also introduce a strategy aimed at minimizing the BLER by joint power allocation with relay selection. The solution demonstrates improved effectiveness in comparison to benchmark methods.

3. To ensure the analytical results are accurate, comprehensive numerical simulations were performed. In addition, the system's performance was evaluated by examining the impact of variables such as the number of antennas at the transmitting source, the packet lengths, and the number of interfering node.

   To emphasize the advancements this paper presents over prior works, we provide Table 1.

Organization: The remaining of the paper is organized as follows: the system model and performance analysis are presented in Section 2 and Section 3, respectively. Section 4 introduces solution for problem of joint optimal power allocation and relay selection. The key findings and conclusion are described in Section 5 and Section 6, respectively.

2. System Model

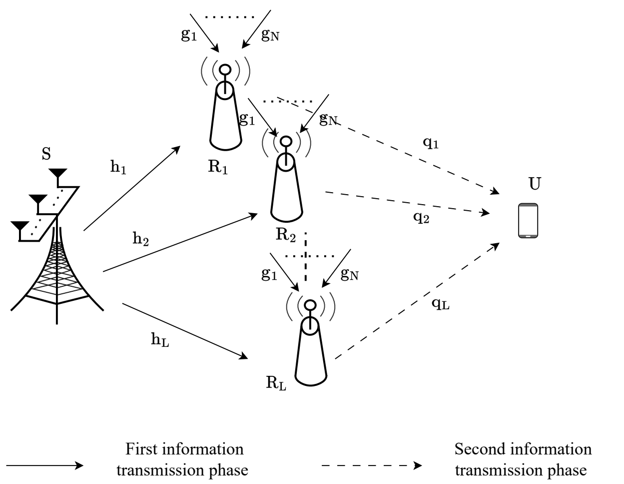

Fig. 1: An illustration of a multiple relay system with short packet communication.

We consider a wireless system including one K antenna source (S), L relay nodes (R_1, ..., R_L) *, and one destination (U). It is assumed that L relays belong to one cluster [23]. All relays are affected by the N interference sources while the destination is unaffected due to the different frequency band usage in different two transmission phases [24, 25]. The communication between S and U takes place in two phases, i.e, the first phase for S- relay transmission and the second phase for relay-U transmission.

In this system, S applies beamforming technique for data transmission. In the first phase, The received signal at l-th relay, i.e., R_l with $l \in \{1, ..., L\}$ transmitted

*For the convenience of our analysis, it is assumed that the relays are placed close together in location-based clustering and have been pre-selected through a long-term routing process to establish communication from the source to destination

Tab. 1: Key contributions.

Context	[20]	[21]	[22]	This paper
Multi-relay	✓	✓	✓	✓
Co-channel interference				✓
Multi-antenna				✓
SPC		✓	✓	✓
BLER		✓	✓	✓
Optimization			✓	✓

from S, is expressed as

$$y_{\mathrm{R_l}} = \sqrt{P_s}\mathbf{h}_l^{\intercal}\mathbf{w}_l x_s + \sum_{n=1}^{N}\sqrt{P_n}g_{n\mathrm{R_l}}x_n + z_{\mathrm{R_l}}, \quad (1)$$

where $\mathbf{h}_l$ is $K \times 1$ channel vector of the $\mathrm{S}-\mathrm{R_l}$ link, g_n denotes channel coefficient of the n-th interference source - $\mathrm{R_l}$, x_s and x_n are the signal of S and the n-th interfering node, respectively. $z_{\mathrm{R_l}} \sim \mathcal{CN}(0,\sigma^2)$ is Additive white Gaussian noise (AWGN) and $\mathbf{w}_l = \frac{|\zeta_l|}{||\mathbf{h}_l||}$ denotes $K \times 1$ transmit weight vector. $(.)^{\intercal}$ denotes conjugate transpose.

Next, in the second phase, the signal $y_{\mathrm{R_l}}$ first is amplified with the amplification factor

$$G_l = \sqrt{\frac{P_{\mathrm{R_l}}}{\left(P_s||\mathbf{h}_l||^2 + \sum_{n=1}^{N}P_n|g_{n\mathrm{R_l}}|^2 + \sigma_{\mathrm{R}}^2\right)}} \quad (2)$$

in which $P_{\mathrm{R_l}}$ is the transmit power of $\mathrm{R_l}$ and then conveyed to U. Hence, the signal at U transmitted from the l-th relay is expressed as

$$y_{\mathrm{U,l}} = G_l y_{\mathrm{R_l}} q_l + z_{\mathrm{U,l}}, z_{\mathrm{U,l}} \sim \mathcal{CN}(0,\sigma^2), \quad (3)$$

where q_l is the channel coefficient between $\mathrm{R_l}$ and U, $y_{\mathrm{R_l}}$ is given in (1). Next, form of the end-to-end (e2e) SINR of U can be expressed as follow

$$\beta_{\mathrm{U,l}} = \frac{P_s||\mathbf{h}_l||^2|q_l|^2}{|q_l|^2(\sum_{n=1}^{N}P_n|g_{n\mathrm{R_l}}|^2+\sigma^2)+\sigma^2/G_l^2}. \quad (4)$$

Substituting (2) into (4), the e2e SINR becomes new form as [25, 26]

$$\beta_{\mathrm{U,l}} = \frac{XY}{I(Y+1)+X}, \quad (5)$$

where $X = P_{\mathrm{S,l}}||\mathbf{h}_l||^2$, $Y = \frac{P_{\mathrm{R,l}}|q_l|^2}{\sigma^2}$ and $I = \sum_{n=1}^{N}P_n|g_{n\mathrm{R_l}}|^2$.

3. Performance Analysis

In this paper, we assume that S transmits to each relay and each relay transmits to U with the same number of the bit, i.e., $\mathcal{L}$ and the block-length (packet length) or the number of channel use (CU), i.e., $\mathcal{N}$. According to [27], the e2e average BLER for decoding the signal x_s at U via assitance of $\mathrm{R_l}$ with given $\mathcal{L}$ and $\mathcal{N}$, can be approximated by

$$\epsilon_{\mathrm{U,l}} = Q\left(\frac{C(\beta_{\mathrm{U,l}})-r_l}{\sqrt{V(\beta_{\mathrm{U,l}})/\mathcal{N}}}\right), \quad (6)$$

where $Q(u) = \int_u^{\infty}\frac{1}{\sqrt{2\pi}}\epsilon^{-t^2/2}dt$, $C(u) = \log_2(1+u)$ are the Gaussian Q-function, the Shannon capacity, respectively, and $V(u) = \log_2(e)^2(1-1/(1+u))$ is the channel dispersion, $r_l \triangleq \mathcal{L}/\mathcal{N}$. Based on [28], an approximation of $Q\left(\frac{C(\beta_{\mathrm{U,l}})-r_l}{\sqrt{V(\beta_{\mathrm{U,l}})/\mathcal{N}}}\right)$ can calculated as

$$\Psi(\beta_{\mathrm{U,l}}) \approx \begin{cases} 1, & \beta_{\mathrm{U,l}} \le \xi_v, \\ 0, & \beta_{\mathrm{U,l}} \ge \xi_u, \\ \frac{1}{2}-\chi(\beta_{\mathrm{U,l}}-\tau), & \text{otherwise}, \end{cases} \quad (7)$$

where $\chi = \left[2\pi(2^{2r_l}-1)/\mathcal{N}\right]^{-1/2}$, $\tau = 2^r - 1$, $\xi_v = \tau - 1/(2\chi)$, and $\xi_u = \tau + 1/(2\chi)$. By putting (7) into (6), $e_{\mathrm{U,l}}$ can be of the following form

$$\epsilon_{\mathrm{U,l}} \approx \int_0^{\infty}\Psi(\beta_{\mathrm{U,l}})f_{\beta_{\mathrm{U,l}}}(x)dx \approx \chi\int_{\xi_v}^{\xi_u}F_{\beta_{\mathrm{U,l}}}(x)dx, \quad (8)$$

where $f_{\beta_{\mathrm{U,l}}}(.)$ and $F_{\beta_{\mathrm{U,l}}}(.)$ are probability density function (PDF) and cumulative distribution function (CDF) of $\beta_{\mathrm{U,l}}$, respectively.

3.1. CDF Derivation

From (8), in order to determine the BLER of U relating to l-th relay, namely U_l, we need to find CDF of $\epsilon_{U,l}$. Starting with PDFs of the variables. The PDFs of Y and I variables are

$$f_Y(y) = \frac{1}{\Omega_{U,l}} \exp\left(\frac{-y}{\Omega_{U,l}}\right), \Omega_{U,l} = \frac{P_{R,l}\lambda_{U,l}}{\sigma^2_{U,l}}, \quad (9)$$

$$f_I(u) = \frac{1}{\bar{\Omega}^N_{IR,l}} \frac{u^{N-1}}{(N-1)!} \exp\left(\frac{-u}{\bar{\Omega}_{IR,l}}\right), \bar{\Omega}_{IR,l} = \frac{P_l \lambda_{R,l}}{\sigma^2_{U,l}}, \quad (10)$$

respectively. Next, combining the CDF of variable $X = P_{S,l}||\mathbf{h}||^2$ being

$$F_X(x) = 1 - \exp\left(\frac{-x}{\Omega_{S,l}}\right) \sum_{i=0}^{K-1} \frac{1}{i!} \left(\frac{x}{\Omega_{S,l}}\right)^i, \quad (11)$$

with the PDFs of Y and I, the CDF of $\beta_{U,l}$ is obtained as the following **Proposition**.

Proposition 1: The CDF expression of $\beta_{U,l}$ is

$$F_{\beta_{U,l}}(v) = 1 - \sum_{i=0}^{N-1} \sum_{j=0}^{j} \frac{C^i_j \exp\left(\frac{-v}{\Omega_{R,l}}\right) v^{(i+1)} \Omega^{(j-i-1)/2}_{R,l}}{(\bar{\Omega}_{IR,l})^N \Omega^{(j+i+1)/2}_{S,l} i!(N-1)!} \quad (12)$$

$$\times \frac{\vartheta(N+j+1)\vartheta(N+i)\exp\left(\frac{\bar{\vartheta}^2}{2\bar{\theta}}\right)\bar{\theta}^{L+(j+i)/2}}{\bar{\vartheta}} W_{-N-(i+j)/2,(j-i+1)/2}\left(\frac{\bar{\vartheta}^2}{\bar{\theta}}\right),$$

where $C^i_j = \binom{i}{j}$, $\bar{\theta} = v/\Omega_{S,l} + 1/\bar{\Omega}_{IR,l}$, $\bar{\vartheta} = \sqrt{(v^2+v)/(\Omega_{S,l}\Omega_{R,l})}$.

Proof:

From (4), the CDF of $\beta_{U,l}$ is calculated as

$$\begin{aligned} F_{\beta_{U,l}}(v) &= \Pr\left[\frac{XY}{X+I(Y+1)} < v\right] \\ &= 1 - \Pr\left[X > \frac{vI(Y+1)}{Y-v}, Y > v\right] \quad (13) \\ &= 1 - \int_v^\infty \int_0^\infty \left[1 - F_X\left(\frac{vu(y+1)}{y-v}\right)\right] \\ &\quad \times f_Y(y) dy f_I(u) du \\ &\overset{*}{=} 1 - \left[\int_0^\infty \int_0^\infty \sum_{i=0}^{N-1} \frac{\left(\frac{(v^2+wv+v)u}{w}\right)^i}{i!(\Omega_{S,l})^i \Omega_{R.l}} \right. \\ &\quad \times \exp\left(\frac{-v(w+v+1)u}{\Omega_{S,l} w}\right) \quad (14) \\ &\quad \left. \times \exp\left(-\frac{(w+v)}{\Omega_{R,l}}\right) dw f_I(u) du\right], \end{aligned}$$

where $*$ presents the change of variable as $(w = y - v)$. With $\left(\frac{(v^2+wv+v)u}{w}\right)^i = \sum_{j=0}^i \binom{i}{j} v^i (v+1)^{(i-j)} w^{(j-i)}$ and after some steps of arrangement, Eq. (13) can be in a form as

$$F_{\beta_{U,l}}(v) = 1 - \left[\int_0^\infty \sum_{i=0}^{N-1} \sum_{j=0}^{i} C^i_j \frac{\exp\left(\frac{-v}{\Omega_{R,l}} - \frac{vu}{\Omega_{S,l}}\right)}{i!(\Omega_{S,l})^i \Omega_{R,l}} \right. \quad (15)$$

$$\times v^i (v+1)^{(i-j)} u^i \times \underbrace{\int_0^\infty w^{(j-i)} \exp\left(-\frac{v(v+1)u}{\Omega_{S,l} w} - \frac{w}{\Psi_{R,l}}\right) dw}_{Q_u}$$

$$\left. f_I(u) du\right].$$

Determining Q_u by basing on [29, Eq. (3.471.9)] and then putting into Eq. 15, we obtain

$$F_{\beta_{U,l}}(v) = 1 - \left[\sum_{i=0}^{N-1} \sum_{j=0}^{j} \frac{C^i_j \exp\left(\frac{-v}{\Omega_{R,l}}\right) v^{(i+1)} \Omega^{(j-i-1)/2}_{R,l}}{(\bar{\Omega}_{IR,l})^N \Omega^{(j+i+1)/2}_{S,l} i!(N-1)!} \right. \quad (16)$$

$$\times \int_0^\infty 2u^{(N+(j-i)/2-1/2)} \exp\left(-\left(\frac{v}{\Omega_{S,l}} + \frac{1}{\bar{\Omega}_{IR,l}}\right) u\right)$$

$$\left. \times K_{(j-i+1)}\left(2\sqrt{\frac{(v^2+v)u}{\Omega_{S,l}\Omega_{R,l}}}\right) du\right].$$

Based on [29, Eq. (6.643.3)], the expression $F_{\beta_{U,l}}(v)$ is obtained in (12). The proof is completed. ■

3.2. Average BLER

It is a challenge for determine the average BLER based on (8). To tackle this challenge while ensuring high accuracy and low complexity, we employ a method that utilizes the first-order Riemann integral approximation $\int_{x_1}^{x_2} f(q)dq = (x_2 - x_1) f(\frac{x_1+x_2}{2}) dq$. The average BLER of U, l is attained as

$$\epsilon_{U,l} = (\xi_u - \xi_v) F_{\beta_{U,l}}\left(\frac{\xi_u + \xi_v}{2}\right). \quad (17)$$

3.3. Asymptotic analysis

When $P_{S,R} \to \infty$, the SINR of U relating to l-th relay becomes as

$$\beta^\infty_{U,l} = \frac{XY}{IY + X}, \quad (18)$$

Then, carrying out the step in the *Proof* of the **Proposition 1**, the CDF of $\beta^\infty_{U,l}$ can be expressed as

$$F^{\infty}_{\beta_{\mathrm{U,l}}}(v) = 1 - \sum_{i=0}^{N-1}\sum_{j=0}^{j} \frac{C_j^i \exp\left(\frac{-v}{\Omega_{\mathrm{R,l}}}\right) v^{(i+1)} \Omega_{\mathrm{R,l}}^{(j-i-1)/2}}{(\bar{\Omega}_{\mathrm{IR,l}})^N \Omega_{\mathrm{S,l}}^{(j+i+1)/2} i!(N-1)!} \tag{19}$$

$$\times \frac{\vartheta(N+j+1)\vartheta(N+i)\exp\left(\frac{\bar{\vartheta}^2}{2\bar{\theta}}\right)\bar{\theta}^{L+(j+i)/2}}{\bar{\vartheta}_{asm}} W_{-N-(i+j)/2,(j-i+1)/2}\left(\frac{\bar{\vartheta}^2_{asm}}{\bar{\theta}}\right),$$

where $\bar{\vartheta}_{asm} = \sqrt{v^2/(\Omega_{\mathrm{S,l}}\Omega_{\mathrm{R,l}})}$.

Next, we have the approximated expression of the average BLER of U as

$$\epsilon^{\infty}_{\mathrm{U,l}} = (\xi_u - \xi_u) F^{\infty}_{\beta_{\mathrm{U,l}}}\left(\frac{\xi_u + \xi_v}{2}\right). \tag{20}$$

4. Joint Power control and Relay Selection Problem

In this section, we provide a solution for problem of joint optimal power allocation and relay selection (JOPA-RS). The problem is with aiming at minimizing the BLER can be stated as

$$(\mathrm{P}_1): \mathrm{l}^* = \underset{\mathrm{l}\in\{1,2,\ldots,\mathrm{L}\}}{\operatorname{argmin}} \min_{\{P_{\mathrm{S,l}},P_{\mathrm{R,l}}\}} \epsilon_{\mathrm{U,l}}(P_{\mathrm{S,l}}, P_{\mathrm{R,l}}) \tag{21}$$
$$\text{s.t. } P_{\mathrm{S,l}} + P_{\mathrm{R,l}} \le P_T,$$
$$P_{\mathrm{S,l}} \ge 0,\ P_{\mathrm{R,l}} \ge 0,$$

where P_T denotes the transmit power budget of both the source and the relay. Note that for a given relay l, $\epsilon_{\mathrm{U,l}}$ is a decreasing function with respect to $\beta_{\mathrm{U,l}}$ as the following *Lema*.

Lemma 1: $\epsilon_{\mathrm{U,l}}$ is a decreasing function with respect to $\beta_{\mathrm{U,l}}$.

Proof: We denote $f(\beta_{\mathrm{U,l}}) = \frac{C(\beta_{\mathrm{U},l}) - r_{\mathrm{U,l}}}{\sqrt{V(\beta_{\mathrm{U,l}})/\kappa}}$. Then, after taking the first derivative of $\epsilon_{\beta_{\mathrm{U},l}}$ w.r.t $\beta_{\mathrm{U,l}}$, we have

$$\frac{\partial\epsilon_{\beta_{\mathrm{U,l}}}}{\partial\beta_{\mathrm{U,l}}} = \frac{\partial\epsilon_{\beta_{\mathrm{U,l}}}}{\partial f(\beta_{\mathrm{U,l}})}\frac{\partial f(\beta_{\mathrm{U,l}})}{\partial\beta_{\mathrm{U,l}}} - \frac{e^{-(f^2(\beta_{\mathrm{U,l}})/2)}}{\sqrt{(2\pi)}}\zeta \tag{22}$$

where $\zeta = \frac{\sqrt{\nu}\left(1 - \frac{\ln 2(\log_2(1+\beta_{\mathrm{U,l}}) - \nu/\kappa)}{(1+\beta_{\mathrm{U,l}})^2 - 1}\right)}{\sqrt{(1+\beta_{\mathrm{U,l}})^2 - 1}}$. Note that $\zeta(\beta_{\mathrm{U,l}}) \ge \frac{\sqrt{\nu}\left(1 - \frac{\ln(1+\beta_{\mathrm{U,l}})}{(1+\beta_{\mathrm{U,l}})^2 - 1}\right)}{\sqrt{(1+\beta_{\mathrm{U,l}})^2 - 1}}$. Let define $\eta(u) = \left(1 - \frac{\ln(u)}{u^2 - 1}\right)$ where $u = 1 + \beta_{\mathrm{U,l}} \ge 1$. Now we check the first derivative of $\eta(u)$ w.r.t u, i.e., $\eta'(u) = \frac{\Psi(u)}{u(u+1)^2}$, where $\Psi(u) = u^2 - 1 - 2u^2 \ln u$. Note that $\Psi(u)$ is a decreasing function because $\Psi'(u) = -4u\ln(u) \le 0$ for $u \ge 1$. This results in $\Psi(u) \le \Psi(1) = 0$, then leads to $\eta'(u) \le 0$ or $\eta(x)$ is a decreasing function of u and $\eta(u) \le \eta(1)$ for $u \ge 1$. Beside, based on L'Hopital rule, $\operatorname{Lim}_{u->1} \eta(u) = 1/2$, one goes to

$$\zeta(\beta_{\mathrm{U,l}}) \ge \frac{\sqrt{\nu}}{2\sqrt{(1+\beta_{\mathrm{U,l}})^2 - 1}} \ge 0. \tag{23}$$

This means that $(\epsilon_{\beta_{\mathrm{U,l}}})' \le 0$. The proof is completed. ■

From *Lemma 1*, Problem (P_1) can be rewritten as

$$(\mathrm{P}_2): \mathrm{l}^* = \underset{\mathrm{l}\in\{1,2,\ldots,\mathrm{L}\}}{\operatorname{argmax}} \max_{\{P_{\mathrm{S,l}},P_{\mathrm{R,l}}\}} \beta_{\mathrm{U,l}}(P_{\mathrm{S,l}}, P_{\mathrm{R,l}}) \tag{24}$$
$$\text{s.t. } P_{\mathrm{S,l}} + P_{\mathrm{R,l}} \le P_T,$$
$$P_{\mathrm{S,l}} \ge 0,\ P_{\mathrm{R,l}} \ge 0.$$

To address the joint problem, we can divide it into two sub-problems carried out in two steps presented in following subsections.

4.1. Optimal Power Allocation

In the first step, the first sub-problem focuses on determining the optimal power allocation for each relay. For the l-th relay, the optimal power allocation (OPA) problem can be expressed as

$$(\mathrm{P}_3): \max_{\{\mathrm{P_{S,l}},\mathrm{P_{R,l}}\}} \beta_{\mathrm{U,l}}(P_{\mathrm{S,l}}, P_{\mathrm{R,l}}) \tag{25}$$
$$\text{s.t. } P_{\mathrm{S,l}} + P_{\mathrm{R,l}} \le P_T,$$
$$P_{\mathrm{S,l}} \ge 0,\ P_{\mathrm{R,l}} \ge 0.$$

Firstly, we check the first order derivatives of $\beta_{\mathrm{U,l}}$ w.r.t P_{S} and P_{R}. Due to $\frac{\partial\beta_{\mathrm{U,l}}}{\partial P_{\mathrm{S,l}}} = \frac{IY(Y+1)||\mathbf{h}_l||^2}{(||\mathbf{h}_l||^2 P_{\mathrm{S,l}} + IY + I)^2} > 0$ and $\frac{\partial\beta_{\mathrm{U,l}}}{\partial P_{\mathrm{R,l}}} = \frac{\frac{|q_l|^2}{\sigma^2} X(I+X)}{I(\frac{|q_l|^2}{\sigma^2} P_{\mathrm{R,l}} + 1) + X^2} > 0$, $\beta_{\mathrm{U,l}}$ are increasing functions of $P_{\mathrm{S,l}}$ and $P_{\mathrm{R,l}}$. Therefore, to maximize $\beta_{\mathrm{U,l}}$ transmit power budget need to be maximized, i.e., $P_{\mathrm{S,l}} + P_{\mathrm{R,l}} = P_T$. Upon replacing $P_{\mathrm{R,l}} = P_T - P_{\mathrm{S,l}}$ in Problem (**P**3), it is confirmed that $\beta_{\mathrm{U,l}}$ is a concave function, as indicated by its second order derivative being negative, i.e.,

$$\frac{\partial^2\beta_{\mathrm{U,l}}}{\partial P^2_{\mathrm{S,l}}} = \frac{-2||\mathbf{h}_l||^2 \frac{|q_l|^2}{\sigma^2}\left(\frac{|q_l|^2}{\sigma^2} P_T I + I\right)\left(||\mathbf{h}_l||^2 P_T + I\right)}{\left(\frac{|q_l|^2}{\sigma^2} I(P_T - P_{\mathrm{S,l}}) + ||\mathbf{h}_l||^2 P_{\mathrm{S,l}} + I\right)^3} < 0. \tag{26}$$

Hence, the optimal value of $P^*_{\mathrm{S,l}}$ is determined by solving $\frac{\partial\beta_{\mathrm{U,l}}}{\partial P_{\mathrm{S,l}}} = 0$. It takes the following form

$$P^*_{\mathrm{S,l}} = \begin{cases} \frac{\sqrt{\Psi_1\Psi_2} + \Psi_2}{I|q_l|^2/\sigma^2 - I||\mathbf{h}_l||^2}, & I|q_l|^2/\sigma^2 - ||\mathbf{h}_l||^2 > 0, \\ \frac{-\sqrt{\Psi_1\Psi_2} + \Psi_2}{I|q_l|^2/\sigma^2 - I||\mathbf{h}_l||^2}, & I|q_l|^2/\sigma^2 - ||\mathbf{h}_l||^2 < 0, \end{cases} \tag{27}$$

where $\Psi_1 = ||\mathbf{h}_l||^2 P_T + I$, $\Psi_2 = I|q_l|^2/\sigma^2 P_T + I$. Finally, we get

$$P^*_{\mathrm{R,l}} = P_T - P^*_{\mathrm{S,l}}. \tag{28}$$

4.2. Relay Selection Scheme

In this subsection, we find the optimal relay which obtains the minimum BLER based on the previously calculated optimal values of $P^*_{\mathrm{R,l}}$ and $P^*_{\mathrm{S,l}}$. In other words, in the second step, the second sub-problem is to choose the index of the best relay that achieves the maximum SINR with the optimal power allocation achieved in the first step. The sub-problem in this step can be expressed as

$$l^* = \underset{l\in\{1,2,\ldots,L\}}{\operatorname{argmax}} \beta^*_{\mathrm{U,l}}\left(P^*_{\mathrm{S,l}}, P^*_{\mathrm{R,l}}\right). \tag{29}$$

The entire solution for JOPA-RS is summarized as in **Algorithm 1**.

Algorithm 1 Joint Power Allocation and Relay Selection Algorithm

1: For each relay l, calculate the optimal power allocation, i.e., $P^*_{\mathrm{S,l}}$, $P^*_{\mathrm{R,l}}$ based on Eq. (27) .
2: Determine the maximum of each $\beta_{\mathrm{U,l}}$ with $P^*_{\mathrm{S,l}}$, $P^*_{\mathrm{R,l}}$.
3: Select the best relay l^* based on Eq. (29).

5. Numerical results

Some parameters for simulation are set as follows: the transmit power of each interfer: 2.8 (dB)[25]; the number of transmitted bits: 100 (bits) [1]; the number of packet length: 200 (channel uses) (CUs) [30]; distance between the l-th co-channel interference and R: random in 20 (m) to 50 (m); distance between S and R: 30 (m); distance between R and D: 50 (m). In the figures, the terms 'Sim:opt' and 'Sim:eq.' in the legend denote the simulation results for Optimal Power Allocation (OPA), as outlined in **Algorithm 1**, and for Equal Power Allocation (EPA), wherein the transmit power budget equally allocates power to both the source and the relay.

Fig. 2 illustrates change of the average BLER with transmit power budget, P_T. In this scenario, the number of users, i.e., K, is established at 4, the number of relay, i.e., L, is set at 3, and the number of interfers is within the set 1, 3, 8. It is observed that the simulation and theoretical results align closely. Obviously, when transmit power increases, the average BLER decreases. In this Figure, the affect of the co-channel interference on the performance is shown. Furthermore, the comparison of two power allocation strategies, OPA and EPA, demonstrates that the OPA scheme contributes to the enhancement of system performance.

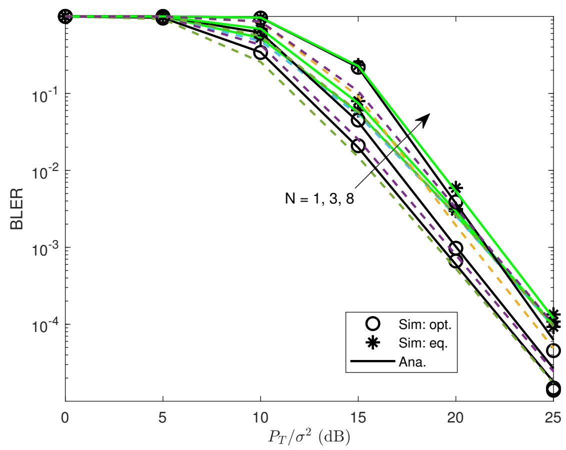

Fig. 2: Average BLER versus transmit power budget, P_T, $K = 4$, $L = 3$.

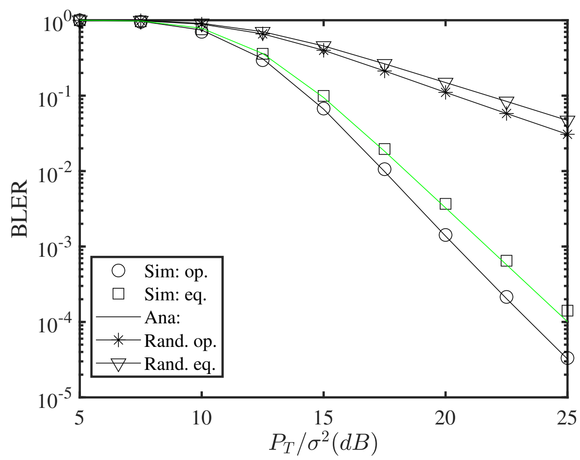

Fig. 3: Comparison of joint power allocation and relay selection schemes, $K = 4$, $N = 3$, and $L = 3$.

Fig. 3 compares two approaches: the first is a joint power allocation and optimal relay selection scheme, and the second is a joint power allocation with random relay selection, for a system with $K = 4$, $N = 3$, and $L = 3$. Each scheme, we also introduce two solutions of power allocation are OPA and EPA. It is apparent that the OPA solution consistently surpasses EPA across all schemes. Moreover, it is clear that the system using random relay selection exhibits the worst BLER performance for both OPA and EPA. The Figure confirms the superiority of JOPA-RS scheme because the scheme carries out OPA and optimal relay selection.

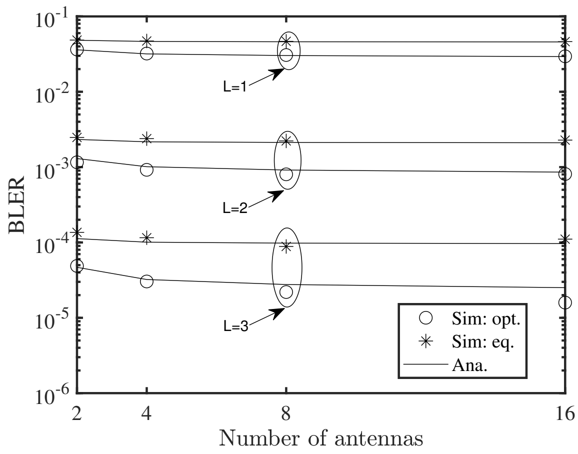

Fig. 4: Average BLER versus the number of antenna at the source, $N = 3$, $L = 3$.

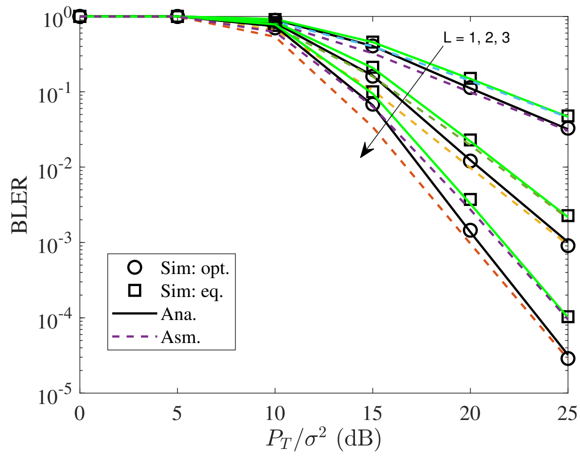

Fig. 6: Average BLER versus the number of interfers, $K = 4$, $N = 3$.

Fig. 4 presents the affect of the number of antenna at the source on the average BLER. The system's performance improves when $K = 4$; however, for $K > 4$, there is a negligible increase in the average BLER. This phenomenon occurs because, although increasing the number of antennas improves the transmission quality of the S − R link, there is no corresponding enhancement for the R−U link. The Figure also shows that the JOPA-RS solution yields benefits in scenarios involving multiple relays.

Fig. 6 illustrates the advantages of selecting more relays, as evidenced by the improved BLER with an increasing number of relays. We can see that BLER in case of $L = 3$ is better than that in case of $L = 1$. This is because increasing the number of relays enhances the ability to select the most suitable relay.

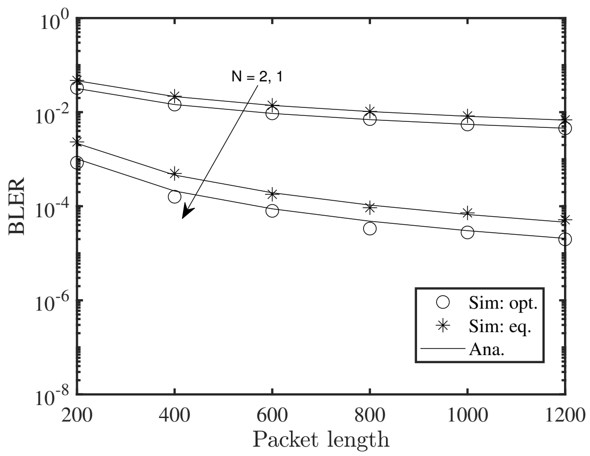

Fig. 5: Average BLER versus packet length, $K = 4$, $N = 3$.

Fig. 5 plots the affect of packet length on the average BLER with $K = 4$. It is observed that an increase in packet length correlates with an improvement in the average BLER. When the packet length exceeds 200 CUs, there is a gradual decrease in the average BLER. In addition, the Figure reaffirms the effectiveness of the JOPA-SR solution.

6. Conclusion

The paper discussed the implementation of short packet communications within a relaying system that is subject to co-channel interference at the relay. To assess performance, the system's BLERs were derived in forms of both closed-form and asymptotic expressions. Furthermore, an joint optimal power allocation and relay selection method was proposed to achieve the lowest BLER for the system. The effectiveness of this solution was demonstrated by comparing it to a scheme with equal power allocation scheme, highlighting the advantages in BLER performance. Furthermore, system performance was evaluated through key metrics such as the number of antennas at the source, packet length, and the number of co-channel interference nodes. Specifically, increasing the number of source antennas will result in a plateau in performance gains. Exploration of additional antennas at the relay to improve performance, the effects of co-channel interference at both the relay and destination, and the role of imperfect channel state information will be left for future works.

Author Contributions

The main contributions of Uyen-Vu Le ANH and Tien-Tung NGUYEN were to create the main ideas and execute performance evaluation by extensive simulations, while those of Xuan-Phuong NGUYEN were to discuss, create, and advise the main ideas and performance evaluation.

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