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Link Selection in Buffer-Aided Cooperative Networks for Green IoT

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ABSTRACT In this paper, the link selection algorithm in buffer-aided cooperative networks with multiple co-channel interferers for green internet of things (IoT) is investigated. In the considered system, the relay node selects the better link from the first and the second hop with the help of buffers. We evaluate the effects of the system parameters by deriving the analytical analysis as well as the asymptotic results on the exact expressions of the outage probability. The impacts of system parameters, such as the predefined target rate, the priority-outage tradeoff parameter, the buffer length and the number of interferers are evaluated in different setup scenarios. Considerable performance gains can be obtained compared with the classical decode-and-forward relaying networks. Simulation results are provided to verify the theoretical analysis.

INDEX TERMS Buffer-aided, co-channel interference, link selection, outage probability, cooperative networks.

I. INTRODUCTION

In the recent years, there has been an explosively development in wireless communication and the transmission rate [1]–[3]. To support the demand of high data-rate transmission, many new wireless techniques have been proposed [4]–[6]. With the deployment of the fifth-generation (5G) wireless communication systems, the associated applications such as green internet of things (IoT) have attracted a lot of attention from both the academy and industry [7]–[10]. To support the application of 5G and green IoT, many new techniques are proposed to improve the capacity of the system. Among these new techniques, Buffer-aided cooperative networks, which was shown to enhance the quality of the classical wireless relaying system, have attracted much attention from both academic and industry groups. With the help of buffers, the better link can be selected for transmission. For example, authors in [11] proposed the max-max scheme to selects the relay with the strongest SNR between the first and the second hops. Moreover, without delay constraints, the max-link scheme is introduced in ref. [12], which selects the best link in an available set. To reduce the packet delay, authors in [13] choosed the second hop with priority than the first hop, and analyzed the outage probability and the average packet delay of the proposed scheme compared with conventional schemes. As an extended work, considering the weight, the quality and the priority of the links, ref. [14] proposed a combined metric to select the best relay node. The proposed scheme is evaluated in terms of outage probability, the delay and the throughput of the system.

On the other hand, the presence of the co-channel interference, which is usually introduced by frequency reuse or other wireless systems, may greatly lower the QoS of the networks [15]–[18]. Specifically, authors in [19] derived the closed-form expression for the outage probability when the interfering signals experience Nakagami-m fading. With the presence of multiple independent interferers at the destination, the outage performance of an

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amplify-and-forward two-hop two-user channel is studied in [20]. While, authors in [21] investigated the effects of co-channel interference on the security performance in multiple relaying networks.

However, to the best of our knowledge, there is little literature studying the effect of the co-channel interference for the buffer-aided cooperative networks with link selection. Motivated by that, in this paper, we will discuss the link selection algorithm for buffer-aided cooperative networks with co-channel interference. Assisted by the buffers, the relay node can select the better link from the first and the second hop to relieve the effects of the interferers. We evaluate the effects of the system parameters by deriving the analytical analysis as well as the asymptotic results on the exact expressions of the outage probability.

The main contributions of this paper are summarized as follows:

- We employ the buffer-aided relay combining technique for the co-channel interference networks, which can exploit the benefits of both branches in the system and meanwhile reduce the implementation complexity.
- We provide an exact outage probability expression for the buffer-aided co-channel interference networks, in order to evaluate the transmission performance achieved by the buffer-aided protocol.
- We present new results for the asymptotic outage probability of the buffer-aided co-channel interference networks. These asymptotic expressions enable us to determine the major factors that regulate the transmission performance in the high transmit power region.

The impacts of system parameters, such as the predefined target rate, the priority-outage tradeoff parameter, the buffer length and the number of interferers are evaluated in different setup scenarios.

Notations: We use $\mathcal{CN}(\mu, \sigma^2)$ to represent the circularly symmetric complex Gaussian random variable with mean μ and variance σ^2, $f_X(x)$ and $F_X(x)$ denote the probability density function (PDF) and cumulative distribution function (CDF) of a random variance x, respectively, diag($\mathbf{A}$) is a row vector consisting of all diagonal elements of $\mathbf{A}$, and $R-D$ denotes the link from R to D.

II. SYSTEM MODEL

Fig.1 depicts the model of the two-slot buffer-aided relaying system. In the considered system, the source node S transmits message to the destination node D. We assume that no direct links exist from the source node to the destination node [22]–[24], while a relay can be used to assist the information transmission with decode-and-forward mode. All nodes are assumed to be equipped with single antenna.

Moreover, the relay holds a data buffer of finite size L [25], [26], which can be used to store packets decoded correctly from the source. Specifically, the relay is corrupted by M co-channel interferers $\{I_m, m \in [1, 2, \ldots, M]\}$ with fixed transmission power P_I. Let $h_{SR} \in \mathcal{CN}(0, \beta_1)$, $h_{RD} \in \mathcal{CN}(0, \beta_2)$ and $h_{I_mR} \in \mathcal{CN}(0, \epsilon)$ denote the instantaneous channel fading coefficients of the wireless links of $S-R$, $R-D$ and $I_m - R$, respectively. All links are quasi-static Rayleigh block fading and stochastically independent between each other.

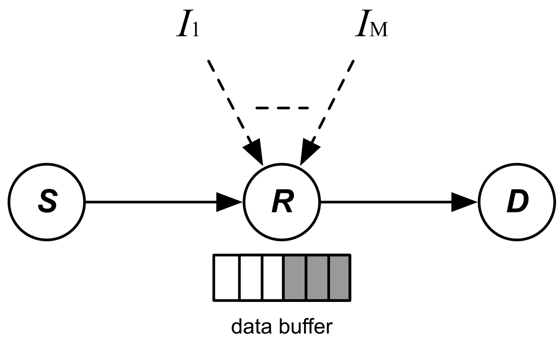


FIGURE 1. System model of two-slot buffer-aided relaying networks.

The transmission protocol is equally slotted and the target rate is predefined as r_0 bit per channel use (BPCU). Let $\varphi_k \in [0, 1, \ldots, L]$ denotes the occupied buffer length in the k-th time slot, with initial status as $\varphi_0 = 0$. To obtain better outage performance, the max-link scheme as in [12] is adopted, where in each slot either the $S-R$ link or the $R-D$ link is selected based on the quality of the links. Specifically, if $\varphi_k = 0$, only the $S-R$ link is available. While in the case of $\varphi_k = L$, $R-D$ is selected. If φ_k is partial filled, the better link of $S-R$ and $R-D$ will be active. Moreover, the status of φ_k can be changed as follows: (a) the φ_k increases by one, if the $S-R$ link is selected and the relay can decode the packet correctly. (b) the φ_k decreases by one, if the $R-D$ link is active and the destination node can decode the packet successfully. (c) if neither link can successfully decode the packet, the outage occurs and the φ_k remains unchanged. Note that the retransmission signal can be sent through an error-free dedicated feedback channel with ACK mechanism.

III. LINK SELECTION AND PERFORMANCE ANALYSIS

For the case that $S-R$ link is selected, the received signal at relay can be given by

$$y_R = \sqrt{P_S} h_{SR} x_S + \sum_{m=1}^{M} \sqrt{P_I} h_{I_mR} x_m + n_R, \tag{1}$$

where P_S and P_I are the transmission power of S and I_m, respectively. $x_S \in \mathcal{CN}(0, 1)$ and $x_m \in \mathcal{CN}(0, 1)$ are the transmission symbols of the source and interferer. $n_R \in \mathcal{CN}(0, N_0)$ denotes the additive white Gaussian noise (AWGN) received at R [27]–[29], where the effect of noise on the communication systems can be found in the literature such as the works [30]–[32].

Thus, the signal-to-interference-plus-noise ratio (SINR) at R can be written as

$$\gamma_R = \frac{u P_S}{\sum_{m=1}^{M} w_m P_I + N_0}$$

$$= \frac{u\overline{P}_S}{1+\overline{P}_I\sum_{m=1}^{M} w_m} = \frac{u\overline{P}_S}{1+z}, \quad (2)$$

where $\overline{P}_S = P_S/N_0$ and $\overline{P}_I = P_I/N_0$ are the average transmission SNR of source and interferers. $u = |h_{SR}|^2$ and $w_m = |h_{I_mR}|^2$ represent the channel fading gains of the links of $S-R$ and I_m-R, respectively. $z = \sum_{m=1}^{M} w_m\overline{P}_I$ is the total interference power received at R.

According to the Sum Distribution Theorem in [33], we can obtain the PDF of z as follows

$$f_z(z) = \frac{\mu^{-M}}{(M-1)!}z^{M-1}e^{-z/\mu}, \quad z \geq 0, \quad (3)$$

the CDF of z is

$$F_z(z) = 1-\sum_{k=0}^{M-1}\frac{1}{k!}\left(\frac{z}{\mu}\right)^k e^{-z/\mu}. \quad (4)$$

and the characteristic function of z is

$$\phi_z(j\omega) = E_z(e^{-j\omega z}) = (1+j\omega\mu)^{-M}, \quad (5)$$

where $\mu = \epsilon\overline{P}_I$.

According to the definition of γ_R in (2), we can obtain the CDF of γ_R as follows

$$\begin{aligned} F_{\gamma_R}(x) &= \Pr[\gamma_R \leq x] = \Pr[\frac{u\overline{P}_S}{z+1} \leq x] \\ &= \Pr[u \leq \frac{xz}{\overline{P}_S}+\frac{x}{\overline{P}_S}] \\ &= E_z[1-e^{-(\frac{xz}{\overline{P}_S\beta_1}+\frac{x}{\overline{P}_S\beta_1})}] \\ &= 1-e^{-\frac{x}{\overline{P}_S\beta_1}}E_z[e^{-\frac{xz}{\overline{P}_S\beta_1}}] \end{aligned} \quad (6)$$

By using the characteristic function of z in (5), we can rewrite $F_{\gamma_R}(x)$ as

$$\begin{aligned} F_{\gamma_R}(x) &= 1-e^{-\frac{x}{\overline{P}_S\beta_1}}E_z[e^{-\frac{xz}{\overline{P}_S\beta_1}}] \\ &= 1-e^{-x/c_1}\left(1+x\mu/c_1\right)^{-M} \end{aligned} \quad (7)$$

where $c_1 = \beta_1\overline{P}_S$.

Conditioned on that the buffer state is empty, and only $S-R$ link can be selected, the outage probability of this case can be calculated as

$$\begin{aligned} p_{o,SR} &= \Pr\Big[\log_2(1+\gamma_R) < r_0\Big] \\ &= \Pr\big[\gamma_R < \gamma_0\big] \\ &= F_{\gamma_R}(\gamma_0), \end{aligned} \quad (8)$$

where $\gamma_0 = 2^{r_0}-1$.

Note that it's easy to prove that the diversity order of $p_{o,SR}$ is 1 with respect to P_S.

For the case that the buffer is full, and only $R-D$ link can be selected, the received signal at D can be given by

$$y_D = \sqrt{P_R}h_{RD}x_S + n_D, \quad (9)$$

where P_R is the transmission power of R and $n_D \in \mathcal{CN}(0, N_0)$ denotes the AWGN received at D.

Thus, the SNR at D can be expressed as

$$\gamma_D = \frac{vP_R}{N_0} = v\overline{P}_R, \quad (10)$$

with its CDF and PDF as

$$F_{\gamma_D}(x) = \Pr[v \leq \frac{x}{\overline{P}_R}] = 1-e^{-\frac{x}{\beta_2\overline{P}_R}} = 1-e^{-\frac{x}{c_2}}, \quad (11)$$

$$f_{\gamma_D}(x) = \frac{1}{\beta_2\overline{P}_R}e^{-\frac{x}{\beta_2\overline{P}_R}} = \frac{1}{c_2}e^{-\frac{x}{c_2}}, \quad (12)$$

where $\overline{P}_R = P_R/N_0 = \xi P_S/N_0$ is the average transmission SNR of R, and $c_2 = \beta_2\overline{P}_R = \rho\beta_2\overline{P}_S$.

Similarly, conditioned on that the $R-D$ link is selected, the outage probability of this case can be expressed as

$$\begin{aligned} p_{o,RD} &= \Pr\Big[\log_2(1+\gamma_D) < r_0\Big] \\ &= \Pr\big[\gamma_D < \gamma_0\big]. \\ &= F_{\gamma_D}(\gamma_0). \end{aligned} \quad (13)$$

By using equ.(11), it's easy to prove that the diversity order of $p_{o,RD}$ is 1 with respect to P_S.

As a benchmark, we can obtain the outage probability of the classical DF relaying networks without buffer (i.e. $L = 0$) as follows:

$$\begin{aligned} p_{o,ref} &= \Pr\Big[\log_2(1+\min\{\gamma_R, \gamma_D\}) < r_0\Big] \\ &= \Pr\big[\min\{\gamma_R, \gamma_D\} < \gamma_0\big] \\ &= F_{\gamma_R}(\gamma_0)+F_{\gamma_D}(\gamma_0)-F_{\gamma_R}(\gamma_0)F_{\gamma_D}(\gamma_0). \end{aligned} \quad (14)$$

We will compare the performance of the buffer-aided cooperative networks with the classical DF relaying networks by exact outage probability as well as the simulation results in the following sections.

Consider the link selection algorithm, we assume that if the SINR of the first hop is greater than that of the second hop by α times, i.e. $\gamma_R > \alpha\gamma_D$, the first hop is activated. Otherwise, the second hop is selected for transmission.

Given the function definition that

$$J(\theta) = \int_{\theta}^{\infty} F_{\gamma_R}(\alpha x)f_{\gamma_D}(x)dx. \quad (15)$$

According to the definitions of γ_R and γ_D, we have the following equation:

$$\begin{aligned} J(\theta) &= \int_{\theta}^{\infty} F_{\gamma_R}(\alpha x)f_{\gamma_D}(x)dx. \\ &= \int_{\theta}^{\infty}[1-e^{-\alpha x/c_1}\left(1+\alpha x\mu/c_1\right)^{-M}]f_{\gamma_D}(x)dx \\ &= 1-F_{\gamma_D}(\theta)-\frac{1}{c_2c_3^M}G(\theta, c_4, \frac{1}{c_3}, M), \end{aligned} \quad (16)$$

where α is a priority-outage tradeoff parameter used in the link selection algorithm, $c_3 = \alpha\mu/c_1, c_4 = \alpha/c_1 + 1/c_2,$

and $G(\theta, c, \beta, n)$ is defined as eq.(3.353) in ref. [34], i.e.,

$$G(\theta, c, \beta, n) = \int_{\theta}^{\infty} \frac{e^{-cx}}{(x+\beta)^n}dx = e^{-\theta c}\sum_{k=1}^{n-1}\frac{(k-1)!(-c)^{n-k-1}}{(n-1)!(\theta+\beta)^k} - \frac{(-c)^{n-1}}{(n-1)!}e^{\beta c}Ei[-(\theta+\beta)c], \quad n \geq 2 \quad (17)$$

and $Ei(x)$ is the exponential integral function defined in eq.(8.211) of ref. [34] as

$$Ei(-x) = -\int_{x}^{\infty} \frac{e^{-t}}{t}dt. \quad (18)$$

If the buffer of R is partial filled, the probability of that φ_k increases by one can be written as

$$p_+ = \Pr\left[\gamma_R > \alpha\gamma_D, \gamma_R > \gamma_0\right] = \Pr\left[\gamma_R > \alpha\gamma_D > \gamma_0\right] + \Pr\left[\gamma_R > \gamma_0 > \alpha\gamma_D\right], \quad (19)$$

By using the CDF of γ_R and γ_D on the first item in (19), we have

$$p_{+,1} = \Pr\left[\gamma_R > \alpha\gamma_D > \gamma_0\right] = \Pr\left[\gamma_R > \alpha\gamma_D, \gamma_D > \gamma_0/\alpha\right] = \int_{\gamma_0/\alpha}^{\infty}\left[1 - F_{\gamma_R}(\alpha x)\right]f_{\gamma_D}(x)dx = [1 - F_{\gamma_D}(\frac{\gamma_0}{\alpha})] - \int_{\frac{\gamma_0}{\alpha}}^{\infty} F_{\gamma_R}(\alpha x)f_{\gamma_D}(x)dx \quad (20)$$

Consider the second item in (19), due to the independence between γ_R and γ_D, we obtain

$$p_{+,2} = \Pr\left[\gamma_R > \gamma_0 > \alpha\gamma_D\right] = \Pr\left[\gamma_R > \gamma_0\right]\Pr\left[\gamma_D < \gamma_0/\alpha\right] = \left[1 - F_{\gamma_R}(\gamma_0)\right]F_{\gamma_D}(\frac{\gamma_0}{\alpha}). \quad (21)$$

Applying (16) on (20) and substituting (20) and (21) into (19), we obtain

$$p_+ = 1 - F_{\gamma_R}(\gamma_0)F_{\gamma_D}(\frac{\gamma_0}{\alpha}) - \int_{\frac{\gamma_0}{\alpha}}^{\infty} F_{\gamma_R}(\alpha x)f_{\gamma_D}(x)dx = 1 - F_{\gamma_R}(\gamma_0)F_{\gamma_D}(\frac{\gamma_0}{\alpha}) - J(\frac{\gamma_0}{\alpha}). \quad (22)$$

And the probability of that φ_k decreases by one can be expressed as

$$p_- = \Pr\left[\gamma_R \leq \alpha\gamma_D, \gamma_D > \gamma_0\right] = \int_{\gamma_0}^{\infty} F_{\gamma_R}(\alpha x)f_{\gamma_D}(x)dx = J(\gamma_0). \quad (23)$$

Thus, for the case that the buffer is neither empty nor full, the outage probability can be expressed as

$$p_{o,l} = 1 - (p_+ + p_-) = F_{\gamma_R}(\gamma_0)F_{\gamma_D}(\frac{\gamma_0}{\alpha}) + J(\frac{\gamma_0}{\alpha}) - J(\gamma_0). \quad (24)$$

We use p^{SR} to denote the probability that the first hop is selected, i.e.,

$$p^{SR} = \mathbf{Pr}[\gamma_R > \alpha\gamma_D] = 1 - \int_0^{\infty} F_{\gamma_R}(\alpha x)f_{\gamma_D}(x)dx = 1 - J(0). \quad (25)$$

On the other hand, the probability that the second hop is activated can be expressed as

$$p^{RD} = 1 - p^{SR} = J(0). \quad (26)$$

Let $\mathbf{A}$ represents the state transition matrix of the buffer length, and the entries of $\mathbf{A}$ can be defined as follows

$$\mathbf{A}_{i+1,j+1} = \Pr\left[\varphi_{k+1} = i|\varphi_k = j\right], \quad \forall i, j \in [0, L]. \quad (27)$$

By using the previous mathematical derivations, we can rewrite $\mathbf{A}_{i,j}$ as

$$A_{i+1,j+1} = \begin{cases} p_{o,SR} & \text{If } i = 0,\ j = 0 \\ (1 - p_{o,SR}) & \text{If } i = 1,\ j = 0 \\ p_- & \text{If } i = j-1,\ 0 < j < L \\ p_{o,l} & \text{If } i = j,\ 0 < j < L \\ p_+ & \text{If } i = j+1,\ 0 < j < L \\ (1 - p_{o,RD}) & \text{If } i = L-1,\ j = L \\ p_{o,RD} & \text{If } i = L,\ j = L \\ 0 & \text{Else.} \end{cases} \quad (28)$$

From the definition of the state transition matrix, we can easily obtain that $\sum_{i=1}^{L+1} \mathbf{A}_{i,j} = 1, \forall j$. Thus, the transition probability matrix is column stochastic, and the stationary distribution can be given as

$$\pi = (A - I + B)^{-1}b, \quad (29)$$

where $b = (1, 1, \ldots, 1)^T$, $B_{i,j} = 1, \forall i, j$, $\pi = (\pi_1, \pi_2, ..., \pi_{L+1})^T$ and $\pi_{i+1} = \Pr[\varphi_k = i, k \to \infty]$.

And the system outage probability can be calculated as

$$P_O = \text{diag}(\mathbf{A})\pi = \sum_{l=1}^{L+1} \mathbf{A}_{l,l}\pi_l. \quad (30)$$

Since the transition probability matrix $\mathbf{A}$ is reversible [12], by using the global balance equation, we have

$$\pi_i \mathbf{A}_{j,i} = \pi_j \mathbf{A}_{i,j}, \quad \forall i, j. \quad (31)$$

Specifically, if $i = 1$, we have

$$\pi_2 = \pi_1 \frac{\mathbf{A}_{2,1}}{\mathbf{A}_{1,2}} = \pi_1 \frac{1 - p_{o,SR}}{p_-}. \quad (32)$$

If $2 \leq i \leq L$, we have

$$\pi_{i+1} = \pi_i \frac{\mathbf{A}_{i+1,i}}{\mathbf{A}_{i,i+1}} = \pi_i \frac{p_+}{p_-} = (\frac{p_+}{p_-})^{i-1}\pi_2 = (\frac{p_+}{p_-})^{i-1}(\frac{1 - p_{o,SR}}{p_-})\pi_1 = t_1 t_2^{i-1}\pi_1, \quad (33)$$

where $t_1 = \frac{1-p_{o,SR}}{p_-}$, and $t_2 = \frac{p_+}{p_-}$.

Considering the sum of stationary distribution is always 1, i.e., $\sum_{k=1}^{L+1}\pi_k = 1$, we can calculate the stationary distribution for the empty state as

$$\pi_1 = (1 + t_1\sum_{k=1}^{L} t_2^{k-1})^{-1} = \big(1 + t_1\frac{1-t_2^L}{1-t_2}\big)^{-1}. \quad (34)$$

Thus, the average buffer length can be expressed as

$$\overline{L} = \sum_{i=1}^{L+1}[(i-1)\pi_i]. \quad (35)$$

IV. ASYMPTOTIC OUTAGE PROBABILITY

In order to give a insight into the effects of the system parameters, we present the asymptotic analysis on the exact expressions of the outage probability, where both P_S and P_R are large enough.

Firstly, we will focus on the case of finite buffer length. We assume that $\overline{P}_R = \xi\overline{P}_S, \overline{P}_S \to \infty$. By using the approximation $e^{-x} \approx 1-x$ and $(1+x)^{-M} \approx 1-Mx$ on (7), we can rewrite $F_{\gamma_R}(x)$ as

$$\begin{aligned} F_{\gamma_R}(x) &= 1 - e^{-x/c_1}\big(1 + x\mu/c_1\big)^{-M} \\ &\approx 1 - (1-x/c_1)(1-Mx\mu/c_1) \\ &= \frac{x(1+M\epsilon\overline{P}_I)}{\beta_1\overline{P}_S}. \end{aligned} \quad (36)$$

Thus, if the buffer is empty, the asymptotic outage probability of this state can be expressed as

$$p_{o,SR} = F_{\gamma_R}(\gamma_0) \approx \frac{\gamma_0(1+M\epsilon\overline{P}_I)}{\beta_1\overline{P}_S}. \quad (37)$$

Considering the scenario of interference limited, i.e., $\overline{P}_I \gg 1$, $p_{o,SR}$ can be simplified as

$$p_{o,SR} \approx \frac{\gamma_0 M\epsilon\overline{P}_I}{\beta_1\overline{P}_S}. \quad (38)$$

Similarly, we can rewrite $F_{\gamma_D}(x)$ in (11) as

$$F_{\gamma_D}(x) \approx \frac{x}{c_2} = \frac{x}{\beta_2\overline{P}_R} = \frac{x}{\beta_2\xi\overline{P}_S}, \quad (39)$$

and the asymptotic outage probability for the case that the buffer is full can be expressed as

$$p_{o,RD} = F_{\gamma_D}(\gamma_0) \approx \frac{\gamma_0}{\beta_2\xi\overline{P}_S}. \quad (40)$$

According to the definition of $f_{\gamma_D}(x)$ in (12), using the subsection integral method and applying variable substitution, we can rewrite $J(\theta)$ as

$$\begin{aligned} J(\theta) &\approx \int_{\theta}^{\infty}[\frac{\alpha x}{c_1}(1+M\mu)]f_{\gamma_D}(x)dx \\ &= \frac{\alpha}{c_1}(1+M\mu)(\theta+c_2)e^{-\theta/c_2} \\ &\approx \frac{\alpha\beta_2\xi}{\beta_1}(1+M\epsilon\overline{P}_I)(1-\frac{\theta}{\beta_2\xi\overline{P}_S}) \end{aligned} \quad (41)$$

Particularly, for the case that the transmission power is large enough, i.e., $\overline{P}_S \to \infty$, we obtain

$$J(0) \approx \frac{\alpha\beta_2\xi}{\beta_1}(1+M\epsilon\overline{P}_I) \quad (42)$$

Since $p^{RD} = J(0)$, we can conclude that the probability that the second hop is activated is a linear function with respect to the radio of average link fading power of the second hop to the first hop.

Considering the differential of $J(\theta)$, when the transmission power is large enough, we can have the following approximation

$$\begin{aligned} J(\theta_1) - J(\theta_2) &\approx \int_{\theta_1}^{\theta_2}[\frac{\alpha x}{c_1}(1+M\mu)]f_{\gamma_D}(x)dx \\ &= \frac{\alpha(1+M\mu)}{2c_1c_2}(\theta_2^2-\theta_1^2). \end{aligned} \quad (43)$$

Substituting (36) (39) and (43) into (24), we can obtain the asymptotic outage probability of the state that the buffer is partially occupied as follows

$$\begin{aligned} p_{o,l} &\approx (\frac{\gamma_0}{\overline{P}_S})^2\frac{(1+M\epsilon\overline{P}_I)}{\alpha\beta_1\beta_2\xi} + \frac{\alpha(1+M\epsilon\overline{P}_I)}{2\beta_1\overline{P}_S\beta_2\xi\overline{P}_S}[\gamma_0^2-(\gamma_0/\alpha)^2] \\ &= (\frac{\gamma_0}{\overline{P}_S})^2\frac{(1+M\epsilon\overline{P}_I)}{2\beta_1\beta_2\xi}(\alpha+\frac{1}{\alpha}) \end{aligned} \quad (44)$$

Obviously, $\alpha = 1$ is the global optimal value for $p_{o,l}$.

From the asymptotic expressions on the outage probability for the case that the buffer is either empty or full, we can give the following remarks:

Remark 1: For the case that the buffer is either empty or full, the diversity order of the asymptotic outage probability is 1 with respect to the transmission power.

Remark 2: With empty buffer, in the case that interference power is large enough, the asymptotic outage probability is a linear increasing function with respect to the interference number and average interference power, respectively.

Remark 3: For the case that the buffer is neither empty nor full, the diversity order is 2. Furthermore, the priority-outage tradeoff parameter $\alpha = 1$ is the optimal value for minimization of the outage probability.

Remark 4: Since the outage probability of the case that the buffer is either empty or full is the dominated contribution to the total system outage probability in (30), the diversity order of P_O is 1.

V. SIMULATION RESULTS

In this section, simulation results are provided to verify the theoretical analysis. The impacts of system parameters, such as the predefined target rate r_0, the priority-outage tradeoff parameter α, the buffer length L and the number of interferers M, are evaluated in different setup scenarios. The simulation results are compared with the theoretical analysis as well as the asymptotic results.

Fig.2 and Fig.3 show the effects of the predefined target rate r_0 on the outage probability for the partial occupied state and the system outage probability, respectively. The system

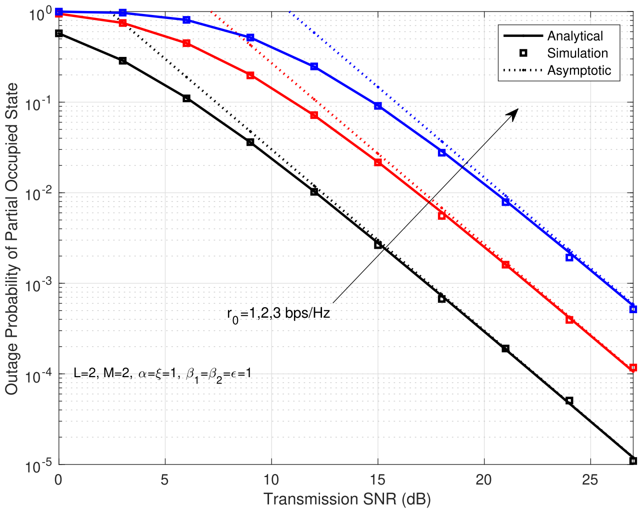


FIGURE 2. Effects of r_0 on the outage probability for the partial occupied state.

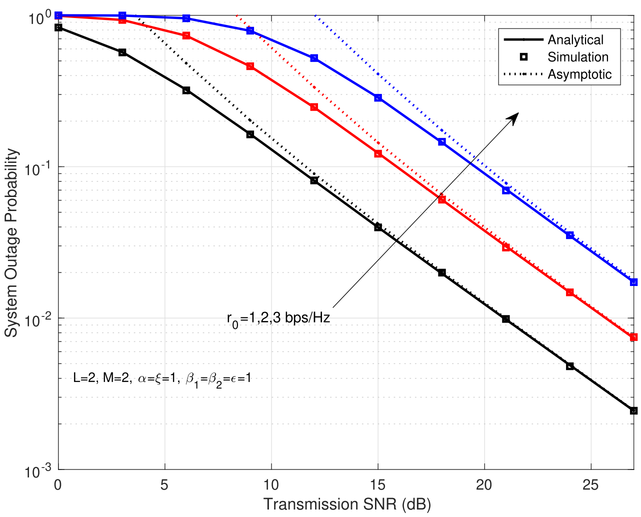


FIGURE 3. Effects of r_0 on the system outage probability.

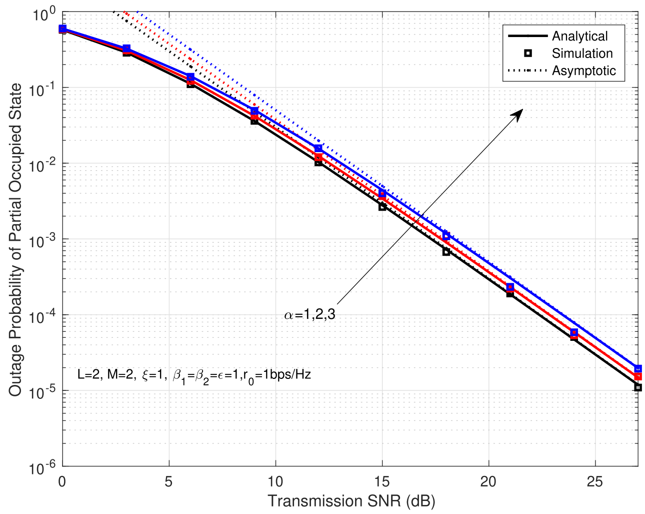


FIGURE 4. Effects of α on the outage probability for the partial occupied state.

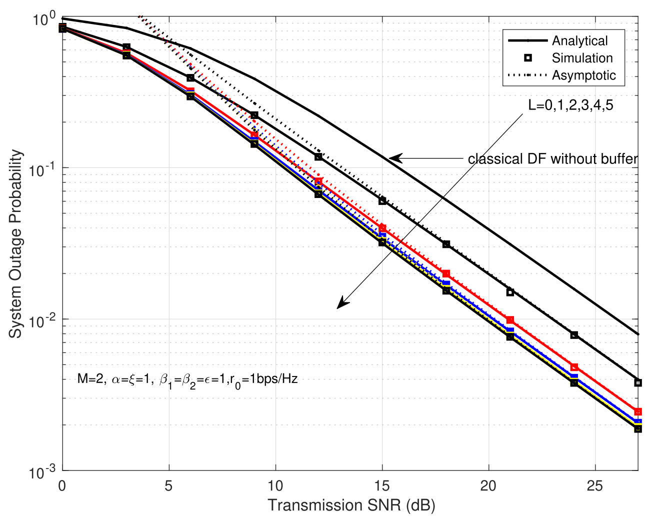


FIGURE 5. Effects of L on the outage probability for the system outage probability.

setup is as follows. The buffer length is 2, the number of interferers is 2, the average channel fading gains are set as $\beta_1 = \beta_2 = \epsilon = 1$, and the priority-outage tradeoff parameter and the power factor are both set as 1, i.e., $\alpha = \xi = 1$, while the predefined target rate r_0 changes from 1 to 3 bps/Hz. The simulation results and the analytical results as well as the asymptotic results are compared in both figures. We can see that the analytical lines match the simulation lines well, and in high SNR regions, converges to the asymptotic ones. Moreover, larger r_0 can results in higher outage probability, while the diversity order remains the same, which is coincident with normal intuition. Specifically, we can conclude that the diversity order is 2 for the partial occupied state, and for the system outage probability, the diversity order is 1.

Fig.4 presents the impacts of the priority-outage tradeoff parameter α on the outage probability for the partial occupied state. The system setup is as follows. $L = M = 2, \xi = 1$, the average channel fading gains are set as $\beta_1 = \beta_2 = \epsilon = 1$, and the predefined target rate r_0 is 1 bps/Hz, while the priority-outage tradeoff parameter changes from 1 to 3. According to the remarks in the theoretical analysis, $\alpha = 1$ is the optimal value for the outage probability. Also, from the figure, we see that the performance curve of $\alpha = 1$ is better that other curves. And the larger α introduces the higher outage probability, which is coincident with the result in eq.(44).

Fig.5 presents the impacts of the buffer length L on the system outage probability. The system setup is as follows. $M = 2, \alpha = \xi = 1$, the average channel fading gains are set as $\beta_1 = \beta_2 = \epsilon = 1$, and the predefined target rate r_0 is set as 1 bps/Hz, while the buffer length changes from 0 to 5 with step 1. Note that $L = 0$ denotes the classical DF relaying networks without buffer. From the figure, we can

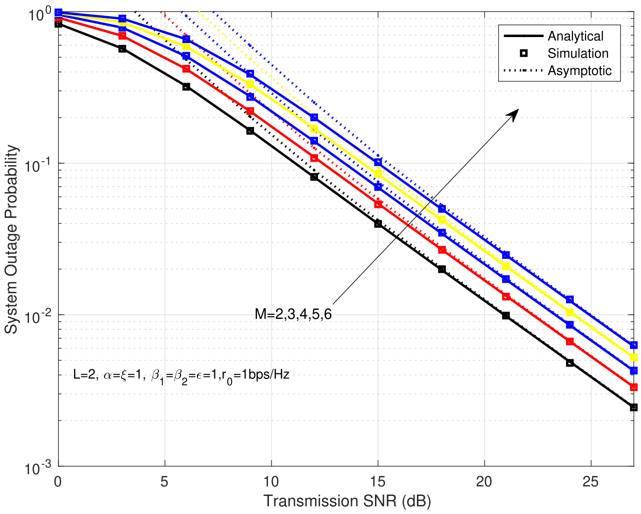


FIGURE 6. Effects of M on the outage probability for the system outage probability.

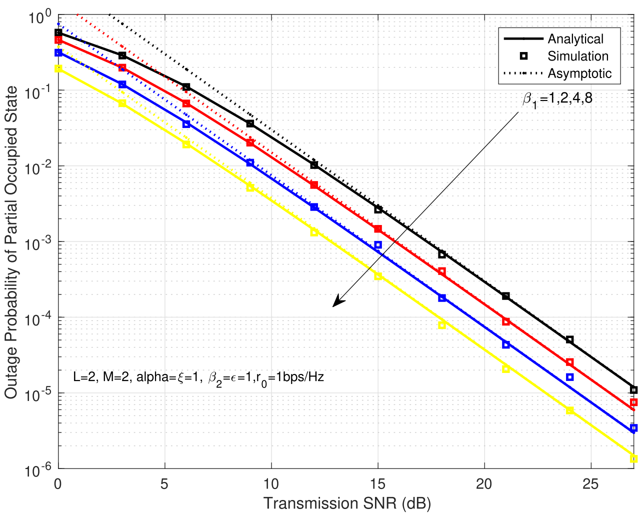


FIGURE 7. Effects of β_1 on the outage probability for the partial occupied state.

see that the large L can improve the performance of the outage probability, while the diversity order is remains 1. The reason is that the bottle-neck of the system is the state of empty or full, and the large L can lower the probability of the state of empty and full, then the outage probability can be enhanced. Furthermore, the buffer-aided cooperative networks can obtain about 3dB gain compared with the classical DF relaying networks. The reason is that the equivalent SNR of the classical DF relaying networks as in equ.(14) is the minimum of the two hops, while in the buffer-aided networks, the equivalent SNR is the maximum of the two hops. Thus, obvious performance gains can be obtained.

Fig.6 presents the impacts of the interferers' number M on the system outage probability. The system setup is as follows. $L = 2, \alpha = \xi = 1$, the average channel fading gains are set as $\beta_1 = \beta_2 = \epsilon = 1$, and the predefined target rate r_0 is set as 1 bps/Hz, while the number of interferers changes from 2 to 6 with step 1. Obviously, the larger M can result in higher outage probability. The reason is that more interference power will be introduced by the larger M, then the outage probability will be higher.

The effects of the average channel fading gain β_1 on the outage probability the partial occupied state is shown in Fig. 7. The system setup is as follows. $L = M = 2, \alpha = \xi = 1$, the average channel fading gains are set as $\beta_2 = \epsilon = 1$, and the predefined target rate r_0 is set as 1 bps/Hz, while β_1 changes from 1 to 8. From this figure, we can see that the larger β_1 can greatly improve the outage probability, while the diversity order is still 2. The reason is that the larger β_1 can improve the quality of the first hop, while the outage probability can be enhanced.

VI. CONCLUSIONS

We investigate the link selection algorithm in buffer-aided cooperative networks with multiple co-channel interference for green IoT. With the help of buffers, the relay node can select the better link from the first and the second hop. In order to give an insight into the effects of the system parameters, we present the analytical analysis as well as the asymptotic results on the exact expressions of the outage probability. Based on the theoretical analysis, we find that the outage probability of the case that the buffer is either empty or full is the dominated contribution to the total system outage probability. Furthermore, the diversity order of the system outage probability is 1. While for the partial occupied state, the diversity order is 2. Simulation results are provided to verify the theoretical analysis. The impacts of system parameters, such as the predefined target rate, the priority-outage tradeoff parameter, the buffer length and the number of interferers are evaluated in different setup scenarios. In future works, we will study the intelligent algorithms such as deep-learning based and reinforcement learning based algorithms to the considered systems [35]–[39], in order to enhance the system transmission performance. Moreover, we will investigate the physical-layer secure techniques for the considered systems [40]–[42], in order to guarantee the security of wireless data transmission.

REFERENCES

[1] F. Shi, J. Xia, Z. Na, X. Liu, Y. Ding, and Z. Wang, "Secure probabilistic caching in random multi-user multi-UAV relay networks," *Phys. Commun.*, vol. 32, pp. 31–40, Feb. 2019.

[2] J. Xia, L. Fan, W. Xu, X. Lei, X. Chen, G. K. Karagiannidis, and A. Nallanathan, "Secure cache-aided multi-relay networks in the presence of multiple eavesdroppers," *IEEE Trans. Commun.*, vol. 67, no. 11, pp. 7672–7685, Nov. 2019.

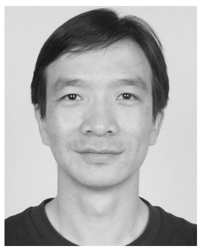
[3] S. Lai, "Intelligent secure communication for cognitive networks with multiple primary transmit power," *IEEE Access*, to be published.

[4] X. Lin, J. Xia, and Z. Wang, "Probabilistic caching placement in UAV-assisted heterogeneous wireless networks," *Phys. Commun.*, vol. 33, pp. 54–61, Apr. 2019.

[5] J. Xia, D. Deng, Y. Rao, D. Li, F. Zhu, and L. Fan, "When distributed switch-and-stay combining meets buffer in IoT relaying networks," *Phys. Commun.*, vol. 38, Feb. 2020, Art. no. 100920.

[6] Y. Guo, "Intelligent offloading strategy design for relaying mobile edge computing networks," *IEEE Access*, to be published.

[7] J. Gong and X. Chen, "Achievable rate region of non-orthogonal multiple access systems with wireless powered decoder," *IEEE J. Sel. Areas Commun.*, vol. 35, no. 12, pp. 2846–2859, Dec. 2017.
[8] J. Gong, X. Chen, and M. Xia, "Transmission optimization for hybrid half/full-duplex relay with energy harvesting," *IEEE Trans. Wireless Commun.*, vol. 17, no. 5, pp. 3046–3058, May 2018.
[9] J. Gong, T.-H. Chang, C. Shen, and X. Chen, "Flight time minimization of UAV for data collection over wireless sensor networks," *IEEE J. Sel. Areas Commun.*, vol. 36, no. 9, pp. 1942–1954, Sep. 2018.
[10] Z. Zhou, J. Feng, L. Tan, Y. He, and J. Gong, "An air-ground integration approach for mobile edge computing in IoT," *IEEE Commun. Mag.*, vol. 56, no. 8, pp. 40–47, Aug. 2018.
[11] A. Ikhlef, D. S. Michalopoulos, and R. Schober, "Max-max relay selection for relays with buffers," *IEEE Trans. Wireless Commun.*, vol. 11, no. 3, pp. 1124–1135, Mar. 2012.
[12] I. Krikidis, T. Charalambous, and J. S. Thompson, "Buffer-aided relay selection for cooperative diversity systems without delay constraints," *IEEE Trans. Wireless Commun.*, vol. 11, no. 5, pp. 1957–1967, May 2012.
[13] Z. Tian, Y. Gong, G. Chen, and J. A. Chambers, "Buffer-aided relay selection with reduced packet delay in cooperative networks," *IEEE Trans. Veh. Technol.*, vol. 66, no. 3, pp. 2567–2575, Mar. 2017.
[14] W. Raza, N. Javaid, H. Nasir, N. Alrajeh, and N. Guizani, "Buffer-aided relay selection with equal-weight links in cooperative wireless networks," *IEEE Commun. Lett.*, vol. 22, no. 1, pp. 133–136, Jan. 2018.
[15] E. Balti and M. Guizani, "Mixed RF/FSO cooperative relaying systems with co-channel interference," *IEEE Trans. Commun.*, vol. 66, no. 9, pp. 4014–4027, Sep. 2018.
[16] X. Lai, W. Zou, D. Xie, X. Li, and L. Fan, "DF relaying networks with randomly distributed interferers," *IEEE Access*, vol. 5, pp. 18909–18917, 2017.
[17] D. Kudathanthirige and G. A. A. Baduge, "Massive MIMO configurations for multi-cell multi-user relay networks," *IEEE Trans. Wireless Commun.*, vol. 17, no. 3, pp. 1849–1868, Mar. 2018.
[18] J. Hachem, U. Niesen, and S. Diggavi, "Energy-efficiency gains of caching for interference channels," *IEEE Commun. Lett.*, vol. 22, no. 7, pp. 1434–1437, Jul. 2018.
[19] Z. Ni, X. Liu, X. Zhang, and D. Yang, "Outage performance of dual-hop fixed gain amplify-and-forward relaying over Nakagami-m fading with kappa-μ and eta-μ Interference," in *Proc. Veh. Technol. Conf.*, 2013, pp. 1–5.
[20] Y. Su, Y. Li, X. Wu, and L. Liu, "Outage performance for amplify-and-forward two-hop multiple-access channel with noisy relay and interference-limited destination," *IET Commun.*, vol. 12, no. 2, pp. 205–213, Jan. 2018.
[21] L. Fan, X. Lei, N. Yang, T. Q. Duong, and G. K. Karagiannidis, "Secure multiple amplify-and-forward relaying with cochannel interference," *IEEE J. Sel. Topics Signal Process.*, vol. 10, no. 8, pp. 1494–1505, Dec. 2016.
[22] L. Fan, N. Zhao, X. Lei, Q. Chen, N. Yang, and G. K. Karagiannidis, "Outage probability and optimal cache placement for multiple amplify-and-forward relay networks," *IEEE Trans. Veh. Technol.*, vol. 67, no. 12, pp. 12373–12378, Dec. 2018.
[23] J. Xia, "Cache-aided mobile edge computing for B5G wireless communication networks," *EURASIP J. Wireless Commun. Netw.*, vol. 2020, p. 15, Dec. 2020.
[24] B. Lu, "Interference suppression by exploiting wireless cache in relaying networks for B5G communications," *Phys. Commun.*, 2020.
[25] W. Huang, "Multi-antenna processing based cache-aided relaying networks for B5G communications," *Phys. Commun.*, 2020.
[26] C. Li, "Cache-enabled physical-layer secure game against smart UAV-assisted attacks in B5G noma networks," *EURASIP J. Wireless Commun. Netw.*, vol. 2020, no. 1, p. 7, 2020.
[27] C. Li, Y. Xu, J. Xia, and J. Zhao, "Protecting secure communication under UAV smart attack with imperfect channel estimation," *IEEE Access*, vol. 6, pp. 76395–76401, 2018.
[28] R. Zhao, "Deep reinforcement learning based mobile edge computing for intelligent Internet of Things," *IEEE Access*, to be published.
[29] Z. Zhao, "Intelligent mobile edge computing with pricing in Internet of Things," *IEEE Access*, to be published.
[30] X. Lai, L. Fan, X. Lei, J. Li, N. Yang, and G. K. Karagiannidis, "Distributed secure switch-and-stay combining over correlated fading channels," *IEEE Trans. Inf. Forensics Security*, vol. 14, no. 8, pp. 2088–2101, Aug. 2019.
[31] X. Wang, "Joint resource allocation for cognitive OFDM-NOMA systems with energy harvesting in green IoT," *IEEE Access*, to be published.
[32] Z. Zhao, "A novel framework of three-hierarchical offloading optimization for MEC in industrial IoT networks," *IEEE Trans. Ind. Informat.*, to be published.
[33] A. Bletsas, H. Shin, and M. Win, "Cooperative communications with outage-optimal opportunistic relaying," *IEEE Trans. Wireless Commun.*, vol. 6, no. 9, pp. 3450–3460, Sep. 2007.
[34] I. Gradshteyn and I. Ryzhik, *Table of Integrals, Series, and Products*, 7th ed. San Diego, CA, USA: Academic, 2007.
[35] G. Liu, Y. Xu, Z. He, Y. Rao, J. Xia, and L. Fan, "Deep learning-based channel prediction for edge computing networks toward intelligent connected vehicles," *IEEE Access*, vol. 7, pp. 114487–114495, 2019.
[36] K. He, "A MIMO detector with deep learning in the presence of correlated interference," *IEEE Trans. Veh. Technol.*, to be published.
[37] M.-S. Baek, S. Kwak, J.-Y. Jung, H. M. Kim, and D.-J. Choi, "Implementation methodologies of deep learning-based signal detection for conventional MIMO transmitters," *IEEE Trans. Broadcast.*, vol. 65, no. 3, pp. 636–642, Sep. 2019.
[38] J. Xia, Y. Xu, D. Deng, Q. Zhou, and L. Fan, "Intelligent secure communication for Internet of Things with statistical channel state information of attacker," *IEEE Access*, vol. 7, pp. 144481–144488, 2019.
[39] K. He, "Generic deep learning based linear detectors for MIMO systems over correlated noise environments," *IEEE Access*, to be published.
[40] Y. Xu, J. Xia, H. Wu, and L. Fan, "Q-learning based physical-layer secure game against multiagent attacks," *IEEE Access*, vol. 7, pp. 49212–49222, 2019.
[41] X. Lin, Y. Tang, X. Lei, J. Xia, Q. Zhou, H. Wu, and L. Fan, "MARL-based distributed cache placement for wireless networks," *IEEE Access*, vol. 7, pp. 62606–62615, 2019.
[42] C. Li, W. Zhou, K. Yu, L. Fan, and J. Xia, "Enhanced secure transmission against intelligent attacks," *IEEE Access*, vol. 7, pp. 53596–53602, 2019.



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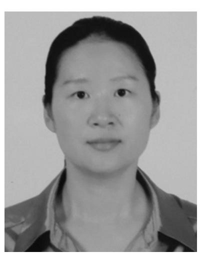

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