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Secrecy Performance of Cooperative Single Carrier Systems with Unreliable Backhaul Connections

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***Abstract*—In this paper, the secrecy outage probability of cooperative cyclic prefixed single carrier (CP-SC) systems with multiple transmitters and unreliable backhaul connections is derived. The transmitters communicate with the destination in the presence of an eavesdropper over two-hop relay channels with non-identical frequency-selective fading. The existence of asymptotic limits on the secrecy outage probability is verified for various backhaul scenarios. For a fixed eavesdropper signal-to-noise ratio (SNR), the limit is found to be exclusively determined by the backhaul reliability. This shows that the diversity gain promised by cooperative CP-SC systems cannot be achieved in the high SNR region. Simulations are presented to verify the derived impact of backhaul reliability on the secrecy performance.**

***Index Terms*—Unreliable backhaul, single carrier transmission, frequency selective fading**

I. Introduction

To meet the unrelenting demand of wireless data traffic, future generation networks are expected to consist of extremely dense deployments of heterogeneous small cells [1]. The accompanying backhaul connections from the backbone to multiple small cell transmitters will also be dense. Due to the prohibitive cost of large-scale wired backhaul deployments, wireless backhaul is emerging as an attractive alternative for future generation networks [2]. In such scenarios, an important consideration is the reliability of backhaul connections due to the stochastic nature of wireless channels. The term *backhaul reliability* can be used to describe deleterious operating conditions that cause link failures [3]–[5] such as network congestion, delay, and lost synchronization.

In this paper, we investigate the physical layer security of a dense wireless network deployment with multiple transmitters connected to a central control unit via unreliable backhaul connections. We assume the transmitters communicate with a destination via a two-hop relay channel in the presence of an eavesdropper. A motivating example for this system is in future heterogeneous networks where the transmitters are small cell base stations providing wireless coverage to an indoor destination user via an intermediate relay. The eavesdropper is a nearby receiver attempting to access information sent by the transmitters and the relay to the destination.

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The physical layer security of a two-hop relay link has been investigated recently in the context of cooperative cyclic prefixed single carrier (CP-SC) systems [6], [7]. CP-SC transmission is a practical strategy to circumvent the frequency selective fading nature of wireless channels with a simple transmitter structure that avoids the high peak-to-average power ratio of orthogonal frequency division multiplexing (OFDM). In frequency selective fading, it has been shown that an overall diversity gain promised by the multi-user and multi-path diversity gains can be achieved by cooperative CP-SC transmission.

This paper extends the existing literature to consider the impact of unreliable backhaul connections on the physical-layer security of cooperative CP-SC systems. The main contributions are summarized as follows. First, we evaluate the end-to-end SNR (e-SNR) of a cooperative CP-SC system with multiple transmitters and frequency selective fading links. We model the unreliable backhaul connections according to a Bernoulli process. Based on the e-SNR statistics, we derive closed-form expressions for the exact and asymptotic secrecy outage probability. The asymptotic limits are found to be exclusively determined by the backhaul reliability parameter. Finally, we present link-level simulations to show that the convergence time to approach the asymptotic limits are determined by the number of transmitters and the multipath diversity gain of the main channel. Notably, the existence of any unreliable backhaul connection will result in a loss of diversity gain.

Notation: $\mathcal{CN}\left(\mu, \sigma^2\right)$ denotes the complex Gaussian distribution with the mean μ and the variance σ^2; $F_{\varphi}(\cdot)$ and $f_{\varphi}(\cdot)$ respectively denote the cumulative distribution function (CDF) and the probability density function (PDF) of the random variable (RV) φ. A length of a vector $\boldsymbol{a}$ is denoted by $\mathbb{L}(\boldsymbol{a})$.

II. System and Channel Model

Fig. 1 shows a block diagram of the system model consisting of a control unit (CU) providing unreliable backhaul to K transmitters communicating with a destination over a two-hop relay link in the presence of an eavesdropper. All the transmitters $(TX_1, \ldots, TX_K)$, eavesdropper E, relay R, and destination D, are equipped with a single antenna. The channel gains are independent and identically distributed (i.i.d.)

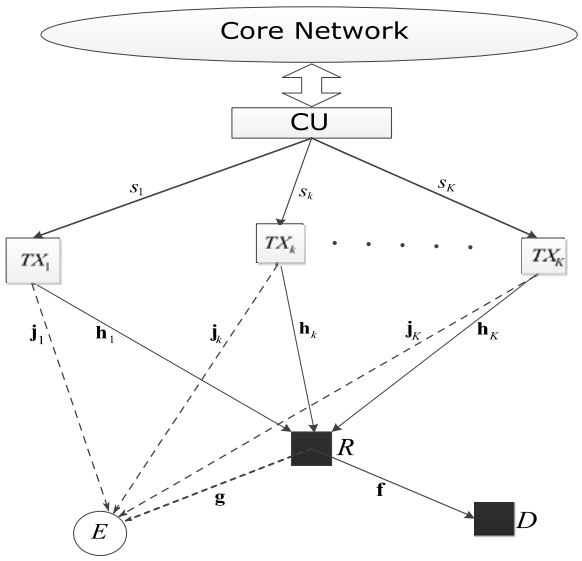

Fig. 1. Example of a cooperative CP-SC system with multiple transmitters connected to the CU via unreliable backhaul connections. Reliability of the kth backhaul is denoted by s_k.

complex Gaussian random variables with zero means and unit variances. The channel model is detailed as follows:

- A channel from the kth transmitter to the relay is denoted by $\boldsymbol{h}_k$ with $\mathbb{L}(\boldsymbol{h}_k) = L_{h,k}$. A path loss component over this channel is denoted by $\alpha_{h,k}$.
- A channel from the relay to the destination is denoted by $\boldsymbol{f}$ with $\mathbb{L}(\boldsymbol{f}) = L_f$. A path loss component over this channel is denoted by α_f.
- A channel from the kth transmitter to the eavesdropper is denoted by $\boldsymbol{j}_k$ with $\mathbb{L}(\boldsymbol{j}_k) = L_{j,k}$ and $\alpha_{j,k}$ for a path loss component over this channel.
- A channel from the relay to the eavesdropper is denoted by $\boldsymbol{g}$ with $\mathbb{L}(\boldsymbol{g}) = L_g$ and α_g for a path loss component over this channel.
- The maximum number of multipaths in the system is defined by $L_{\max} = \max\{\{L_{h,k}, \forall k\}, L_f, \{L_{j,k}, \forall k\}, L_g\}$.

For backhaul reliability, we denote s_k as the probability that TX_k successfully decodes the message from the CU, whereas $1 - s_k$ is the probability that the message is erased. The erasures are assumed to be independent across messages and follow a Bernoulli process $\mathrm{Bernoulli}(1 - s_k)$ [3], with $\mathbb{I}_k$ as the indicator function to model reliability of the kth backhaul such that $Pr(\mathbb{I}_k = 1) = s_k$ and $Pr(\mathbb{I}_k = 0) = 1 - s_k$.

For security enhancement, we adopt transmit antenna selection (TAS) to select a single transmitter in each transmission period with the highest received SNR at the relay. Due to the stochastic nature of the channels, the best transmitter for the relay is a random transmitter for the eavesdroppers [8]. At the eavesdropper, selection combining (SC) is adopted to select the signal with the highest received SNR.

For cooperative CP-SC transmission, we assume M-ary phase-shift keying (MPSK) modulation is applied at the transmitters and the relay to transmit the symbol block $\boldsymbol{x} \in \mathbb{C}^{B\times 1}$. The size of the symbol block is denoted by B. We assume that $E[\boldsymbol{x}] = \boldsymbol{0}$ and $E[\|\boldsymbol{x}\|^2] = \boldsymbol{I}_B$. To prevent inter-block symbol interference (IBSI), an additional CP comprising of P_g symbols from $\boldsymbol{x}$ is appended to the front of $\boldsymbol{x}$ with $P_g \geq L_{\max}$.

In the main channel, the received signal at the relay after the removal of the CP-related signal, is given by

$$\boldsymbol{y}^{\mathrm{R}} = \sqrt{\bar{P}\alpha_{h,k^*}}\boldsymbol{H}^*\mathbb{I}_{k^*}\boldsymbol{x} + \boldsymbol{z}^{\mathrm{R}} \tag{1}$$

where $k^* = \arg\max_{1\leq k\leq K} ||\boldsymbol{h}_k||$ is the index of the selected transmitter, $\bar{P}$ denotes the maximum transmission power at the transmitters, and $\boldsymbol{z}^{\mathrm{R}} \sim \mathcal{CN}(\boldsymbol{0}, \sigma_n^2\boldsymbol{I}_B)$ is the additive noise vector. Due to CP-SC transmission, $\boldsymbol{H}^*$ is represented by the right circulant matrix [9]; that is, $\boldsymbol{H}^*$ is specified by the corresponding channel vector $\boldsymbol{h}_{k^*}$ with additional zeros to have the same size as $\boldsymbol{x}$. Similarly, the received signal at the destination is given by

$$\boldsymbol{y}^{\mathrm{D}} = \sqrt{P_R\alpha_f}\boldsymbol{F}\boldsymbol{x} + \boldsymbol{z}^{\mathrm{D}} \tag{2}$$

where $\boldsymbol{F}$ is a right circulant matrix, which is determined by the channel vector $\boldsymbol{f}$ and additional zeros, and $\boldsymbol{z}^{\mathrm{D}} \sim \mathcal{CN}(\boldsymbol{0}, \sigma_n^2\boldsymbol{I}_B)$. The transmit power at the relay is P_R.

In the eavesdropper's channel, the received signal from the selected k^*-th transmitter is given by

$$\boldsymbol{y}^{\mathrm{E},1} = \sqrt{\bar{P}\alpha_{j,k^*}}\mathbb{I}_{k^*}\boldsymbol{J}_{k^*}\boldsymbol{x} + \boldsymbol{z}^{\mathrm{E},1} \tag{3}$$

where $\boldsymbol{J}_{k^*}$ is the right circulant matrix, which is determined by $\boldsymbol{j}_{k^*}$ and additional zeros, and $\boldsymbol{z}^{\mathrm{E},1} \sim \mathcal{CN}(\boldsymbol{0}, \sigma_n^2\boldsymbol{I}_B)$. Similarly, the received signal from the relay is given by

$$\boldsymbol{y}^{\mathrm{E},2} = \sqrt{P_R\alpha_g}\boldsymbol{G}\boldsymbol{x} + \boldsymbol{z}^{\mathrm{E},2} \tag{4}$$

where $\boldsymbol{G}$ is the right circulant matrix, which is determined by $\boldsymbol{g}$ and additional zeros, and $\boldsymbol{z}^{\mathrm{E},2} \sim \mathcal{CN}(\boldsymbol{0}, \sigma_n^2\boldsymbol{I}_B)$.

III. Derivation of the e-SNR

According to Eqs. (1)-(2), and using the properties of the right circulant matrix [9], the normalized SNRs in the main channel are defined as follows:

$$\lambda^{\mathrm{R}} \triangleq \bar{P}\tilde{\alpha}_{h,k^*}\mathbb{I}_{k^*}\|\boldsymbol{h}_{k^*}\|^2 \text{ and } \lambda^{\mathrm{D}} \triangleq P_R\tilde{\alpha}_f\|\boldsymbol{f}\|^2 \tag{5}$$

where $\tilde{\alpha}_{h,k^*} \triangleq \alpha_{h,k^*}/\sigma_n^2$ and $\tilde{\alpha}_f \triangleq \alpha_f/\sigma_n^2$. For the DF relaying protocol, the e-SNR of the system is given by [10]

$$\lambda^{\mathrm{DF}} = \min(\lambda^{\mathrm{R}}, \lambda^{\mathrm{D}}). \tag{6}$$

According to Eqs. (3)-(4), the normalized SNRs in the eavesdropping channel is given by

$$\lambda^{\mathrm{E},1} \triangleq \bar{P}\tilde{\alpha}_{j,k^*}\mathbb{I}_{k^*}\|\boldsymbol{j}_{k^*}\|^2 \text{ and } \lambda^{\mathrm{E},2} \triangleq P_R\tilde{\alpha}_g\|\boldsymbol{g}\|^2 \tag{7}$$

where $\tilde{\alpha}_{j,k^*} \triangleq \alpha_{j,k^*}/\sigma_n^2$ and $\tilde{\alpha}_g \triangleq \alpha_g/\sigma_n^2$. Applying the SC protocol, the achievable SNR at the eavesdropper is given by

$$\lambda^{\mathrm{E,max}} \triangleq \max(\lambda^{\mathrm{E},1}, \lambda^{\mathrm{E},2}). \tag{8}$$

A. Statistical Properties of the SNRs of the System

The SNRs λ^{D} and $\lambda^{\mathrm{E},2}$ are distributed according to the chi-squared distribution with different degrees of freedoms (DoFs) [9] determined by the number of multipaths. We denote the distributions of λ^{D} and $\lambda^{\mathrm{E},2}$, respectively, as follows:

$$\lambda^{\mathrm{D}} \sim \chi^2(2L_f, P_R\tilde{\alpha}_f) \text{ and } \lambda^{\mathrm{E},2} \sim \chi^2(2L_g, P_R\tilde{\alpha}_g) \quad (9)$$

where the DoFs are $2L_f$ and $2L_g$, respectively. The corresponding power normalizing constants are $P_R\tilde{\alpha}_f$ and $P_R\tilde{\alpha}_g$. Note that the SNR λ^{R} is the largest of K products of Bernoulli random variables and chi-squared random variables. The corresponding CDF is presented in the following proposition.

Proposition 1: The CDF of the SNR λ^{R} is given by

$$F_{\lambda^{\mathrm{R}}}(x) = 1 + \sum_{k=1}^{K}(-1)^k \Upsilon \prod_{t=1}^{k}\Big(\frac{s_{q_t}}{\ell_t!(\bar{P}\tilde{\alpha}_{h,q_t})^{\ell_t}}\Big)e^{-\beta x}x^{\bar{l}} \quad (10)$$

where $\beta \triangleq \sum_{t=1}^{k}\frac{1}{\bar{P}\tilde{\alpha}_{h,q_t}}$, $\bar{l} \triangleq \sum_{t=1}^{k}\ell_t$, and Υ is defined in Appendix A.

Proof: See Appendix A. ∎

Note that this proposition is applicable to a wide range of scenarios with non-identical frequency selective fading channels, non-identical backhaul reliability, and any degrees of transmitter cooperation. Based on Proposition 1, the CDF of the main channel e-SNR is presented in the following theorem.

Theorem 1: For non-identical frequency selective fading, the CDF of the e-SNR of the main channel in a cooperative CP-SC system is given by (11) at the top of the next page.

Proof: See Appendix B. ∎

Note that our CDF in (11) differs from that derived in [11] because we have considered multiple transmitters connected to the CU via dedicated backhauls with non-identical backhaul reliability and non-identical frequency fading.

Proposition 2: The CDF and PDF of the received SNR in the eavesdropper channel with non-identical frequency fading is derived as

$$\begin{aligned} F_{\lambda^{\mathrm{E,max}}}(x) =& 1 + \Phi e^{-\tilde{\beta}x}x^{\tilde{l}} \text{ and} \\ f_{\lambda^{\mathrm{E,max}}}(x) =& \Phi\Big[\tilde{l}x^{\tilde{l}-1}e^{-\tilde{\beta}x} - \tilde{\beta}x^{\tilde{l}}e^{-\tilde{\beta}x}\Big] \end{aligned} \quad (12)$$

where we define $\tilde{\beta} \triangleq \sum_{t=1}^{n}\frac{1}{P_{q_t}}$, $\tilde{l} \triangleq \sum_{t=1}^{n} r_t$, and

$$\Phi \triangleq \sum_{n=1}^{2}(-1)^n \sum_{q_1=1}^{3-n}\cdots\sum_{q_n=q_{n-1}+1}^{2}\sum_{r_1=0}^{L_{3,q_1}-1}\cdots\sum_{r_n=0}^{L_{3,q_n}-1} \prod_{t=1}^{n}\Big(\frac{\tilde{s}_{q_t}}{r_t!(\tilde{P}_{q_t})^{r_t}}\Big) \quad (13)$$

with

$$\tilde{s}_n = \begin{cases} s_{k^*} & \text{for } n=1 \\ 1 & \text{for } n=2 \end{cases}, \tilde{P}_n = \begin{cases} \bar{P}\tilde{\alpha}_{j,k^*} & \text{for } n=1 \\ P_R\tilde{\alpha}_g & \text{for } n=2 \end{cases}, \quad (14)$$

and

$$L_{3,n} = \begin{cases} L_{j,k^*} & \text{for } n=1 \\ L_g & \text{for } n=2 \end{cases}. \quad (15)$$

Proof: See Appendix C. ∎

IV. Secrecy Outage Probability

In this section, we compute the secrecy outage probability based on the derived SNR distributions of the main channel and eavesdropping channel with non-identical frequency selective fading.

A. Exact Secrecy Outage Probability

The secrecy outage probability is defined as the probability that the instantaneous secrecy rate C_s is below a target threshold R which can be evaluated as [12]

$$\begin{aligned} P_{out} &= Pr(C_s < R) \\ &= \int_0^{\infty} F_{\lambda^{\mathrm{DF}}}(2^{2R}(1+x)-1)f_{\lambda^{\mathrm{E,max}}}(x)dx, \end{aligned} \quad (16)$$

where the instantaneous secrecy rate is given by

$$C_s = \frac{1}{2}\Big[\log_2(1+\lambda^{\mathrm{DF}}) - \log_2(1+\lambda^{\mathrm{E,max}})\Big]^+. \quad (17)$$

In (17), $\log_2(1+\lambda^{\mathrm{DF}})$ is the instantaneous capacity of the main channel, $\log_2(1+\lambda^{\mathrm{E,max}})$ is the instantaneous capacity of the eavesdropper channel, and $[x]^+$ denotes $\max\{0,x\}$. Using (11) and (12), a closed-form expression for (16) is provided in the following theorem.

Theorem 2: The secrecy outage probability of a cooperative CP-SC system with an identical backhaul reliability but non-identical frequency selective fading is given by (18) at the top the next page. In (18), we define $J_R \triangleq 2^{2R}$.

Proof: With the help of (11) and (12), (18) can be readily derived. ∎

Note that this theorem provides an analytical framework to aid the outage probability evaluation/design of a cooperative CP-SC system in terms of key design parameters such as transmitter cooperation, frequency selectivity, and backhaul reliability.

B. Asymptotic Secrecy Outage Probability

At a fixed received SNR of the eavesdropping channels, the existence of limits on the secrecy outage probability is inevitable with unreliable backhauls, which is given by the following theorem.

Theorem 3: For frequency selective fading channels and at a fixed received SNR of the eavesdropping links, an asymptotic secrecy outage probability limit is given by

$$P_{\mathrm{out}}^{\mathrm{as},L} = \prod_{k=1}^{K}(1-s_k). \quad (19)$$

Proof: See Appendix E. ∎

Note that from this theorem we can see that only a set of backhaul reliability levels, $\{s_k\}$, exclusively determines asymptotic limits on the secrecy outage probability. As a special case, for an identical backhaul reliability s, asymptotic performance limits are given by $P_{\mathrm{out}}^{\mathrm{as},L} = (1-s)^K$ and $Pr^{\mathrm{as},L}(C_s > 0) = 1-(1-s)^K$. As $s_k \to 1, \forall k$, we can see $P_{\mathrm{out}}^{\mathrm{as},L} \to 0$ and $Pr^{\mathrm{as},L}(C_s > 0) \to 1$, which corresponds to the conventional system with transmitter cooperation

$$F_{\lambda^{\mathrm{DF}}}(x) = 1 - \sum_{k=1}^{K} \Upsilon(-1)^{k+1} \prod_{t=1}^{k} \left(\frac{s_{q_t}}{\ell_t! (\bar{P}\tilde{\alpha}_{h,q_t})^{\ell_t}} \right) \sum_{l=0}^{L_f-1} \frac{1}{l! (P_R \tilde{\alpha}_f)^l} e^{-x\left(\beta + \frac{1}{P_R \tilde{\alpha}_f}\right)} x^{\bar{l}+l} = 1 - \tilde{F}_{\lambda^{\mathrm{DF}}}(x). \tag{11}$$

$$\begin{aligned} P_{out} =& 1 - \sum_{k=1}^{K} \Upsilon(-1)^{k+1} \prod_{t=1}^{k} \left(\frac{s_{q_t}}{\ell_t! (\bar{P}\tilde{\alpha}_{h,q_t})^{\ell_t}} \right) \sum_{l=0}^{L_f-1} \frac{1}{l! (P_R \tilde{\alpha}_f)^l} \sum_{v=0}^{\bar{l}+l} \binom{\bar{l}+l}{v} (J_R - 1)^{\bar{l}+l-v} J_R^v e^{-(J_R-1)\left(\beta + \frac{1}{P_R \tilde{\alpha}_f}\right)} \\ & \Phi \Big[\tilde{l} \Gamma(v + \tilde{l}) \left(\tilde{\beta} + J_R \beta + \frac{J_R}{P_R \tilde{\alpha}_f} \right)^{-v-\tilde{l}} - \tilde{\beta} \Gamma(v + \tilde{l} + 1) \left(\tilde{\beta} + J_R \beta + \frac{J_R}{P_R \tilde{\alpha}_f} \right)^{-v-\tilde{l}-1} \Big]. \end{aligned} \tag{18}$$

and completely perfect backhauls in their connections. This theorem shows that a lower secrecy outage occurs as the backhaul reliability increases, and $Pr(C_s > 0) = 1$ is not achievable when the backhaul connections are not completely perfect in transporting data. In contrast with existing results for perfect backhauls in [6] and [9], we see that the asymptotic diversity gain promised by cooperative CP-SC transmission is not attainable in frequency selective fading channels with unreliable backhauls. However, from the link simulations, we find that a faster convergence speed arriving at these limits can be obtained in proportional to the achievable diversity gain by the CP-SC transmission.

V. Simulation Results

In the following link simulations, we apply quadrature phase-shift keying (QPSK) modulation to the data symbols. The curves obtained via link-level simulations are denoted by **Ex** whereas analytically derived curves are denoted by **An**. For notational purpose, limits on asymptotic secrecy outage probability under unreliable backhauls is denoted by $P_{\mathrm{out}}^{\mathrm{as},L}$, whereas analytic secrecy outage probability under completely perfect backhauls is denoted by $P_{\mathrm{out}}^{\infty}$. The block size is $B = 64$, $\bar{P} = 1$, and $P_R = \chi_R \bar{P}$ with $0 < \chi_R < 1$. We consider the following scenarios to highlight the impacts of key design parameters of a CP-SC system on the secrecy performance.

- S_1: $s_k = 0.99$, $L_{h,k} = \{2,3\}$, $L_f = 2$, $L_{j,k} = \{1,2\}$, $L_g = 2$, $\chi_R = 0.1$.
- S_2: $s_k = 0.80$, $L_{h,k} = \{1,3\}$, $L_f = 2$, $L_{j,k} = \{1,2\}$, $L_g = 2$, $\chi_R = 0.1$.
- S_3: $s_k = 0.90$, $L_{h,k} = \{1,3\}$, $L_{j,k} = \{1,2\}$, $L_g = 2$, $\chi_R = 0.1$.

For scenarios S_1, and S_2, Fig. 2 shows the secrecy outage probability in terms of transmitter cooperation and backhaul reliability. We can see good agreement between the analytical curves and the link-level simulations. The figure shows that increasing the transmitter cooperation results in less frequent secrecy outages due to a higher received signal power at the destination. For non-identical frequency selective fading, we can also evaluate the secrecy outage probability limits as $\tilde{\alpha}_{h,k} \to \infty$ and $\tilde{\alpha}_f \to \infty$. For scenario S_1, they are, respectively, given by $P_{\mathrm{out}}^{\mathrm{as},L} = 0.01$ and $P_{\mathrm{out}}^{\mathrm{as},L} = 0.0001$

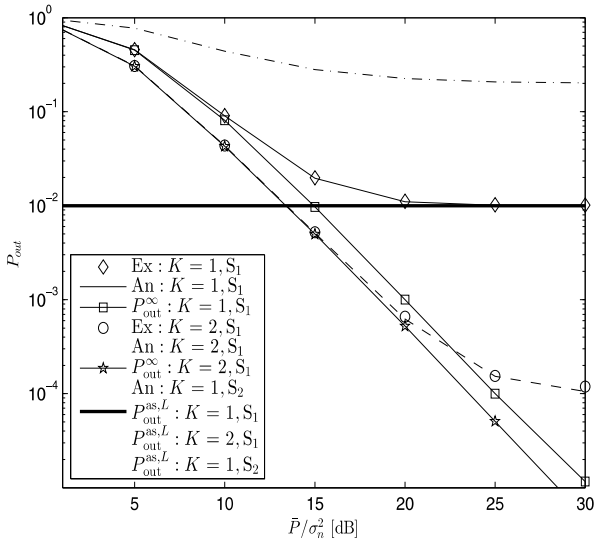

Fig. 2. Secrecy outage probability for various scenarios for $N = 2$ at a fixed value of $P_R \alpha_g$.

for $K = 1$ and $K = 2$, which are exclusively determined by backhaul reliability $s_k = 0.99$ independent of other parameters. For a lower backhaul reliability, $s_k = 0.8$, we observe the existence of a higher limit on the secrecy outage probability, $P_{\mathrm{out}}^{\mathrm{as},L} = 0.2$. We can verify that under completely perfect backhaul connections, the outage diversity gain is $G_d = \min\left(\sum_{k=1}^{K} L_{h,k}, L_f\right)$ by measuring the slope on a $\log - \log$ plot. For example, for scenario S_1, the diversity gain is $G_d = 2$ for $K = 1$ and $K = 2$, since L_f dominates $\min\left(\sum_{k=1}^{K} L_{h,k}, L_f\right)$. Since $\min\left(L_{h,1}, L_f\right) = 1$ for scenario S_2, only $G_d = 1$ can be achieved by the system. Interestingly, we observe that the secrecy outage probability under unreliable backhauls approaches the asymptotic limit with perfect backhaul connections when σ_n^2 is large, whereas the secrecy outage probability approaches the asymptotic limit with unreliable backhaul when σ_n^2 is small. As such, we can classify the operating region into two sub-regions based on the magnitude of σ_n^2. In the unreliable backhaul sub-region,

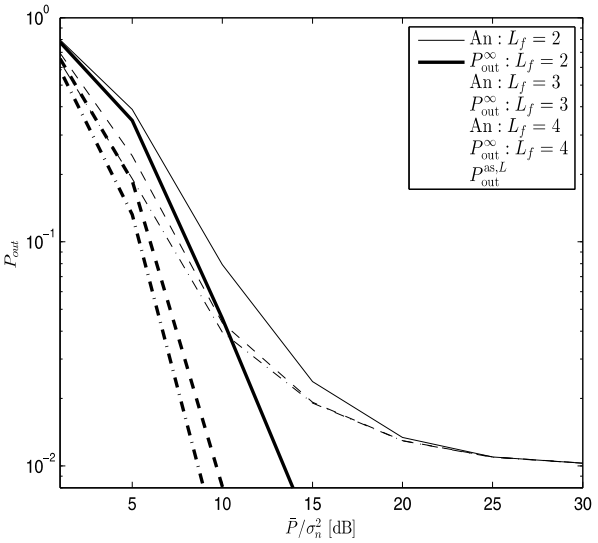

Fig. 3. Secrecy outage probability for various scenarios for $K = 2$ at a fixed value of $P_R\alpha_g$.

the multipath diversity gain is not achievable, whereas in the perfect backhaul sub-region, the multipath diversity gain is achievable. The boundary between the two sub-regions depends on the multipath diversity gain and backhaul reliability.

In Fig.3, for a fixed transmitter cooperation ($K = 2$) and scenario S_3, we investigate the effects of L_f on the secrecy outage probability. We observe that if we increase L_f, then a lower secrecy outage probability is obtained. However, as σ_n decreases, multipath diversity effect decreases due to detrimental effect from unreliable backhauls. Furthermore, based on the asymptotic limit of the secrecy outage probability derived in Theorem 3, we see that the empirical secrecy outage probability from Figs. 2 and 3 approaches its limit specified by $P_{\text{out}}^{\text{as},L} = \prod_{k=1}^{K}(1 - s_k)$.

VI. Conclusions

In this paper, the impact of unreliable backhaul connections has been examined for cooperative single carrier systems with multiple transmitters communicating in the presence of a single passive eavesdropper. Taking into account backhaul reliability, we have derived the distributions of the end-to-end SNR of the main channel and eavesdropping channel under non-identical frequency selective fading channel across the relay and destination. Based on this derivation, we have derived the exact and asymptotic secrecy outage probability. We have shown that irrespective of the parameters such as for the system configuration and frequency selective fading, single carrier systems display a secrecy outage probability limit which is exclusively determined by the backhaul reliability. It has been seen that the conventional promised diversity gain by single carrier system only affects the convergence time arriving at the asymptotic secrecy performance limit.

Appendix A: Derivation of Proposition 1

From the definition of λ^{R} given by

$$\lambda^{\mathrm{R}} = \max_{k=1,\ldots,K} \left(\mathbb{I}_k \bar{P}\tilde{\alpha}_{h,k}\|\boldsymbol{h}_k\|^2\right) \tag{A.1}$$

where $\bar{P}\tilde{\alpha}_{h,k}\|\boldsymbol{h}_k\|^2 \sim \chi^2(2L_{h,k}, \bar{P}\tilde{\alpha}_{h,k})$. Thus, we can derive the PDF of $\mathbb{I}_k\bar{P}\tilde{\alpha}_{h,k}\|\boldsymbol{h}_k\|^2$ as:

$$f_{\mathbb{I}_k\bar{P}\tilde{\alpha}_{h,k}\|\boldsymbol{h}_k\|^2}(x) = (1 - s_k)\delta(x) + \frac{s_k}{\Gamma(L_{h,k})(\bar{P}\tilde{\alpha}_{h,k})^{L_{h,k}}} x^{L_{h,k}-1}e^{-x/\bar{P}\tilde{\alpha}_{h,k}} \tag{A.2}$$

where $\delta(\cdot)$ is the Dirac delta function, and the CDF as:

$$F_{\mathbb{I}_k\bar{P}\tilde{\alpha}_{h,k}\|\boldsymbol{h}_k\|^2}(x) = 1 - \frac{s_k\Gamma(L_{h,k}, x/\bar{P}\tilde{\alpha}_{h,k})}{\Gamma(L_{h,k})}. \tag{A.3}$$

With some manipulations, the CDF of λ^{R} is given by

$$F_{\lambda^{\mathrm{R}}}(x) = 1 + \sum_{k=1}^{K} \Upsilon(-1)^k \prod_{t=1}^{k}\left(\frac{s_{q_t}}{\ell_t!(\bar{P}\tilde{\alpha}_{h,q_t})^{\ell_t}}\right) e^{-\sum_{t=1}^{k}\frac{x}{\bar{P}\tilde{\alpha}_{h,q_t}}} x^{\sum_{t=1}^{k}\ell_t} \tag{A.4}$$

where

$$\Upsilon = \sum_{q_1=1}^{K-k+1} \cdots \sum_{q_k=q_{k-1}+1}^{K} \sum_{\ell_1=0}^{L_{h,q_1}-1} \sum_{\ell_2=0}^{L_{h,q_2}-1} \cdots \sum_{\ell_k=0}^{L_{h,q_k}-1} \tag{A.5}$$

following the same steps as in [13].

Appendix B: Derivation of Theorem 1

We first express $F_{\lambda^{\mathrm{R}}}(x)$ alternatively as:

$$F_{\lambda^{\mathrm{R}}}(x) = 1 - \sum_{k=1}^{K} \Upsilon(-1)^{k+1} \prod_{t=1}^{k}\left(\frac{s_{q_t}}{\ell_t!(\bar{P}\tilde{\alpha}_{h,q_t})^{\ell_t}}\right) e^{-\beta x} x^{\bar{l}}. \tag{B.1}$$

Since $\lambda^{\mathrm{D}} \sim \chi^2(2L_f, P_R\tilde{\alpha}_f)$, $1 - F_{\lambda^{\mathrm{D}}}(x)$ is given by

$$1 - F_{\lambda^{\mathrm{D}}}(x) = e^{-x/P_R\tilde{\alpha}_f} \sum_{l=0}^{L_f-1} \frac{1}{l!}\left(\frac{x}{P_R\tilde{\alpha}_f}\right)^l. \tag{B.2}$$

Now using (B.1) and (B.2), we can yield (11).

Appendix C: Derivation of Proposition 2

The CDF of $\lambda^{\mathrm{E,max}}$ in (10) is given by

$$F_{\lambda^{\mathrm{E,max}}}(x) = F_{\lambda^{\mathrm{E},1}}(x)F_{\lambda^{\mathrm{E},2}}(x) \tag{C.1}$$

where

$$F_{\lambda^{\mathrm{E},1}}(x) = 1 - s_{k^*}e^{-\frac{x}{\bar{P}\tilde{\alpha}_{j,k^*}}} \sum_{r=0}^{L_{j,k^*}-1} \frac{1}{r!}\left(\frac{x}{\bar{P}\tilde{\alpha}_{j,k^*}}\right)^r \text{ and}$$

$$F_{\lambda^{\mathrm{E},2}}(x) = 1 - e^{-\frac{x}{P_R\tilde{\alpha}_g}} \sum_{\tilde{r}=0}^{L_g-1} \frac{1}{\tilde{r}!}\left(\frac{x}{P_R\tilde{\alpha}_g}\right)^{\tilde{r}}. \tag{C.2}$$

We can re-express (C.1) according to

$$F_{\lambda^{\mathrm{E,max}}}(x) \triangleq \prod_{n=1}^{2} F_{\lambda^{\mathrm{E},n,3}}(x) \tag{C.3}$$

where we have combined $F_{\lambda^{\mathrm{E},1}}(x)$ and $F_{\lambda^{\mathrm{E},2}}(x)$ as

$$F_{\lambda^{\mathrm{E,n,3}}}(x) = 1 - \tilde{s}_n e^{-\frac{x}{\tilde{P}_n}} \sum_{r=0}^{L_{3,n}-1} \frac{1}{r!}\Big(\frac{x}{\tilde{P}_n}\Big)^r \tag{C.4}$$

with $\tilde{s}_n$, $\tilde{P}_n$, and $L_{3,n}$ defined in (14), (14), and (15), respectively. We can expand the product term in (C.3) according to similar steps shown in Appendix A which results in the CDF expression in (12), from which the PDF follows directly.

Appendix E: Derivation of Theorem 3

For the asymptotic limit of the CDF of λ^{DF}, we can first derive the asymptotic CDF of λ^{R} in (10) as $\tilde{\alpha}_{h,k} \to \infty$

$$F_{\lambda^{\mathrm{R}}}(x) \approx \prod_{k=1}^{K}(1 - s_k) \tag{E.1}$$

since $\Gamma(L_{h,k}, x/\bar{P}\tilde{\alpha}_{h,k}) \approx \Gamma(L_{h,k})$ as $\tilde{\alpha}_{h,k} \to \infty$. Thus, the asymptotic CDF of λ^{D} as $\tilde{\alpha}_f \to \infty$ is given by

$$F_{\lambda^{\mathrm{D}}}(x) \approx \frac{1}{(L_f)!}\Big(\frac{x}{P_R\tilde{\alpha}_f}\Big)^{L_f}. \tag{E.2}$$

As such, the asymptotic limit for (11) is given by

$$\begin{aligned} F_{\lambda^{\mathrm{DF}}}(x) =& F_{\lambda^{\mathrm{R}}}(x) + F_{\lambda^{\mathrm{D}}}(x) - F_{\lambda^{\mathrm{R}}}(x)F_{\lambda^{\mathrm{D}}}(x) \\ \approx& \prod_{k=1}^{K}(1 - s_k) \end{aligned} \tag{E.3}$$

as $\tilde{\alpha}_{h,k}, \tilde{\alpha}_f \to \infty$. Similarly, as $\tilde{\alpha}_{j,n,k^*} \to \infty$, the CDF of $\lambda^{\mathrm{E,n},1}$ in (C.4) can be approximated as

$$F_{\lambda^{\mathrm{E,n},1}}(x) \approx 1 - s_{k^*} \tag{E.4}$$

since the series expansion of $e^{-\frac{x}{\bar{P}\tilde{\alpha}_{j,n,k^*}}} = \sum_{k=0}^{\infty}(-x)^k/k!(\bar{P}\tilde{\alpha}_{j,n,k^*})^k$ and the summation of $\sum_{r=0}^{L_{j,n,k^*}-1}\frac{1}{r!}\Big(\frac{x}{\bar{P}\tilde{\alpha}_{j,n,k^*}}\Big)^r$ are both dominated by their first terms which is equal to 1. As $\tilde{\alpha}_{g,n} \to \infty$, the CDF of $\lambda^{\mathrm{E,n},2}$ in (C.2) can be approximated as

$$F_{\lambda^{\mathrm{E,n},2}}(x) \approx \frac{1}{(L_{g,n})!}\Big(\frac{x}{P_R\tilde{\alpha}_{g,n}}\Big)^{L_{g,n}}. \tag{E.5}$$

As such, the asymptotic limit of the CDF of $\lambda^{\mathrm{E,max}}$ in (17) is given by

$$F_{\lambda^{\mathrm{E,max}}}(x) \approx \frac{(1 - s_{k^*})^N}{((L_{g,n})!)^N \prod_{n=1}^{N}\tilde{\alpha}_{g,n}^{L_{g,n}}}\Big(\frac{x}{P_R}\Big)^{N(L_{g,n})} \tag{E.6}$$

as $\tilde{\alpha}_{j,n,k^*}, \tilde{\alpha}_{g,n} \to \infty$.

Applying (E.6) and (E.3) to the derivations of the secrecy outage probability results in

$$\begin{aligned} P_{\mathrm{out}}^{\mathrm{as}} =& \int_0^{\infty} F_{\lambda^{\mathrm{DF}}}(2^{2R}(1+x) - 1) f_{\lambda^{\mathrm{E,max}}}(x)dx \\ =& \prod_{k=1}^{K}(1 - s_k) \end{aligned} \tag{E.7}$$

since $f_{\lambda^{\mathrm{E,max}}}(x)$ decays faster than $F_{\lambda^{\mathrm{DF}}}(x)$.

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