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Hybrid-Duplex based Control and Non-Payload Communication Systems for UAVs: An Outage Analysis

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Abstract—In this paper, a hybrid-duplex control and non-payload communication (HBD-CNPC) system is proposed to address spectrum scarcity in unmanned aerial vehicle (UAV) communications. By considering the effects of fading and inter-UAV interference, an outage analysis of the proposed system is conducted. It is shown that the successive interference cancellation (SIC) detector achieves lower outage probability than the interference ignorant (II) detector when the desired signal experiences more severe fading than the interfering signal. It is also demonstrated that the HBD-CNPC system achieves better reliability with longer transmission range and lower transmission requirements over half-duplex (HD) CNPC systems.

Index Terms—Unmanned Aerial Vehicle, Spectrum Efficiency, Control and Non-Payload, Full-Duplex and Hybrid-Duplex systems, Outage Probability, Rician fading, Interference.

I. INTRODUCTION

The recent proliferation of unmanned aerial vehicles (UAVs) has resulted in UAV-related applications towards a wide variety of tasks, including infrastructure inspection and telecommunications relaying [1]. However, the rapid popularity of UAV systems presents a challenge in providing adequate support for control and non-payload communication (CNPC) systems on a common spectrum such as the L-band or the C-band [2]. In particular, spectrum scarcity remains one of the main challenges in UAV systems as both the L-band and C-band are shared by many other systems [3].

To this end, this paper proposes a hybrid-duplex CNPC (HBD-CNPC) system, consisting of half-duplex (HD) UAVs and full-duplex (FD) ground stations (GSs) as a viable first step towards addressing spectrum scarcity. Through the HBD paradigm, the simultaneous communication of CNPC signals on the same spectrum is made possible for both HD and FD nodes [4], with applications in related areas such as in aeronautical communication systems [4]. The concurrent transmission and reception of CNPC signals cause HBD systems to be impaired by self-interference (SI) and inter-UAV interference [4]. The former can be suppressed through SI mitigation architectures in the analog or digital domains [5]. For the latter, interference management strategies, e.g., Interference Ignorant (II) approach and the Successive Inter-

ference Cancellation (SIC) approach, can be employed. For the II approach, interference is treated as noise while the SIC approach successively cancels the interference [4]. It should be noted that spectrum scarcity can also be addressed via an FD-CNPC system, i.e., UAVs and GSs operating in FD mode. However, FD transceiver designs that meet the size, weight, and power restrictions imposed upon UAVs remain as one of the main challenges in such FD-CNPC systems. Therefore, the HBD paradigm presents a pragmatic approach towards solving spectrum scarcity as it enables existing HD-CNPC systems to be retained while improving spectrum utilization.

Apart from SI and inter-UAV interference, CNPC systems may also experience small-scale fading in urban environments [2], [3]. For instance, both Rician and Rayleigh fading were considered in the channel model proposed by Pokkunuru et al. [6], where the capacity of air-to-ground UAV communications was analyzed. Similarly, an outage analysis of air-to-ground UAV communications with relaying was conducted by Azari et al. [7] for Rician fading channels.

Despite related works in the literature, the effects of inter-UAV interference, SI, and Rician K factors on outage probability in HBD-CNPC systems have not been extensively studied. To this end, the major contributions in this paper are as follows.

- Alternative representations of the Rician fading and the Rayleigh fading power probability density functions (PDFs) and cumulative distribution functions (CDFs) are presented.
- Closed-form outage probability expressions of the HBD-CNPC and HD-CNPC systems over Rician and Rayleigh fading channels are presented using alternative PDF expressions.
- Through an outage analysis of the HBD-CNPC system, it is shown that the SIC detector outperforms the II detector when fading on the desired link is more severe than the interfering link. Furthermore, improvements in reliability, transmission power, and transmission range of the HBD-CNPC system over the HD-CNPC system are also demonstrated.

Fig. 1. Unmanned Aerial Vehicle 1 (UAV-1) and Unmanned Aerial Vehicle 2 (UAV-2) operating in HD mode while communicating with the FD ground station (GS).

The organization of this paper is as follows. The system model is introduced in Section II, with the PDF and CDF expressions corresponding to the Rician fading and Rayleigh fading channels presented in Section III. Outage probability expressions are presented in Section IV, with numerical results discussed in Section V before the conclusion of the paper in Section VI.

II. SYSTEM MODEL

The proposed hybrid-duplex control and non-payload communication (HBD-CNPC) system operating in an urban environment is depicted in Fig. 1. In the specific scenario seen in Fig. 1, two half-duplex (HD) UAVs and a full-duplex (FD) ground station (GS) are simultaneously communicating on a common spectrum, e.g., L-band or C-band [2]. The GS and Unmanned Aerial Vehicle 2 (UAV-2) both receive signals from Unmanned Aerial Vehicle 1 (UAV-1). Additionally, operating in FD mode cause the GS to also experience self-interference (SI). As such, SI and inter-UAV interference are present in the proposed HBD-CNPC system. To mitigate the former, SI mitigation measures are assumed at the FD-enabled GS. Also, a mix of Rician and Rayleigh fading are assumed for the UAV communications channels to model the fading environment.

At the GS, let $x_1[t]$ and $x_{si}[t]$ be the signal-of-interest (SOI) transmitted from UAV-1 and SI, respectively, where $x_{si}[t] = x_{gs}[t]$ and $x_{gs}[t]$ is the transmitted signal from the GS. Furthermore, let $h_{1,g}[t]$, h_{si} , and $\tilde{h}_{si} = h_{si} - \hat{h}_{si}$ be the channel between UAV-1 and GS, SI channel gain, and the SI channel gain estimate error, respectively, where $\hat{h}_{si}$ is the imperfect estimation of the SI channel gain. Also, with Rician fading assumed for both h_{si} and $h_{1,g}$, the received signal at GS can be written as [5]:

$$y_{gs}[t] = \sqrt{\Omega_X} h_{1,g}[t] x_1[t] + \sqrt{\Omega_X \alpha_{g,g}} |h_{si}| \gamma_\phi w_\phi[t] + \sqrt{\Omega_X \alpha_{g,g}} \cdot \tilde{h}_{si} |x_{si}[t] + w_g[t], \quad (1)$$

where $w_g[t]$ is the additive white Gaussian noise (AWGN) at GS with zero-mean and variance σ_g^2 , and $w_\phi[t]$ is the Gaussian distributed phase noise term with zero-mean and unit variance, scaled by phase noise strength γ_ϕ^2 [5]. Additionally, $\tilde{h}_{si}$ is modeled as a circularly symmetric zero-mean complex Gaussian random variable (RV) with variance ϵ to model the worst case residual SI [8].

Using the free space path loss model, the average received signal power of the SOI (Ω_X) normalized by σ_g^2 is defined as:

$$\Omega_X = \frac{P_t}{\left(\frac{4\pi \cdot 10^9}{3 \cdot 10^8}\right)^2 \cdot f_c^2 \cdot d_{1,g}^2 \cdot \sigma_g^2}, \quad (2)$$

where P_t , $d_{1,g}$, and f_c are the transmit power (Watts), distance (Km), and carrier frequency (MHz), respectively. In this work, $h_{1,g}[t]$ is chosen as the reference link, with the average received signal power in the other links expressed in terms of $d_{1,g}$ via the multiplicative factor $\alpha_{i,j}$:

$$\alpha_{i,j} = \left(\frac{d_{1,g}}{d_{i,j}}\right)^2, i \in \{g, 1\}, j \in \{g, 2\}. \quad (3)$$

At UAV-2, let $x_{gs}[t]$ and $x_1[t]$ be the SOI transmitted from the GS and the inter-UAV interference from UAV-1, respectively. Also, let $h_{g,2}[t]$ be the channel between GS and UAV-2, and $h_{1,2}[t]$ be the channel UAV-1 and UAV-2. Rayleigh and Rician fading are assumed for $h_{g,2}[t]$ and $h_{1,2}[t]$, respectively. The received signal at UAV-2 is thus:

$$y_2[t] = \sqrt{\Omega_X \alpha_{g,2}} h_{g,2}[t] x_{gs}[t] + \sqrt{\Omega_X \alpha_{1,2}} h_{1,2}[t] x_1[t] + w_2[t], \quad (4)$$

where $\Omega_X \alpha_{g,2}$ and $\Omega_X \alpha_{1,2}$ indicate the average received signal powers of the SOI and interfering signal, respectively, and $w_2[t]$ is the AWGN at UAV-2 with zero-mean and variance σ_2^2 . As interference is present at UAV-2, the interference ignorant (II) and the Successive Interference Cancellation (SIC) interference management approaches are considered in this work.

III. RICIAN AND RAYLEIGH FADING DISTRIBUTION STATISTICS

For a Rician fading channel h , the probability density function (PDF) of $|h|^2$, i.e., Rician fading power PDF, is [9, Table I]:

$$f_{|h|^2}(x) = \frac{K+1}{\Omega} \exp\left(-K - \frac{K+1}{\Omega} x\right) I_0\left(2\sqrt{\frac{K(K+1)}{\Omega}} x\right), \quad (5)$$

where Ω , K , and $I_0(\cdot)$ are the average received power, Rician K factor and the modified zero order Bessel function of the first kind [10], respectively. Let $\alpha_{Rice}(q, \Omega, K, \gamma)$ be defined as:

$$\alpha_{Rice}(q, \Omega, K, \gamma) = (-1)^q \exp(-K) \frac{L_q^{(0)}(K)}{(1+q)!} \left(\frac{(1+K)}{\Omega} \gamma\right)^{q+1}, \quad (6)$$

where γ and $L_q^{(0)}(\bullet)$ represent the threshold value and the q -th degree, zero-order Laguerre polynomials [11]. Then, the cumulative distribution function (CDF) of $|h|^2$ can be expressed as [4]:

$$F_{|h|^2}(\gamma) = \int_0^\gamma f_{|h|^2}(x) dx \approx \sum_{n=0}^{K_{tr}} \alpha_{Rice}(n, \Omega, K, \gamma), \quad (7)$$

Fig. 2. Comparison between the exact PDF and power series approximation equivalent for $\Omega = 1$ and $K_{tr} = 20$.

where K_{tr} is the truncation order. Now, one obtains an alternative expression for $f_{|h|^2}(x)$ as follows:

$$f_{|h|^2}(x) = \frac{\partial}{\partial \gamma} F_{|h|^2}(\gamma) \Big|_{\gamma=x} \approx \sum_{n=0}^{K_{tr}} \alpha_{Rice}(n, \Omega, K, 1)(n+1)x^n. \quad (8)$$

From (6), setting $K = 0$ yields $\alpha_{Ray}(q, \Omega, \gamma)$ which is defined as:

$$\alpha_{Ray}(q, \Omega, \gamma) = \frac{(-1)^q}{(1+q)!} \left(\frac{\gamma}{\Omega} \right)^{q+1}. \quad (9)$$

Then, using the earlier steps, the PDF and CDF for a Rayleigh fading channel h' are given in (10) and (11), respectively, as:

$$f_{|h'|^2}(x) \approx \sum_{n=0}^{K_{tr}} \alpha_{Ray}(n, \Omega, 1)(n+1)x^n \quad (10)$$

$$F_{|h'|^2}(\gamma) \approx \sum_{n=0}^{K_{tr}} \alpha_{Ray}(n, \Omega, \gamma). \quad (11)$$

Fig. 2 shows the comparison of the alternative PDF expressions, given in (8) and (10), with the exact PDFs. The exact PDF for $|h'|^2$ can be obtained from [9, Table I]. Similarly, Fig. 3 shows the alternative CDF expressions, given in (7) and (11), and the exact CDF expressions obtained from [9, Table I]. It is evident from Fig. 2 and Fig. 3 that the alternative PDF and CDF expressions matches closely with the associated exact expressions. Furthermore, expressing the PDFs and CDFs in truncated form enables tractable calculation of outage probabilities, which is shown in the next section.

IV. OUTAGE PROBABILITY DERIVATIONS

In this section, closed-form outage probability expressions for the proposed HBD-CNPC system are presented. Let R_1^{HBD}

Fig. 3. Comparison between the exact CDF and power series approximation equivalent for $\gamma = 1$ and $K_{tr} = 20$.

and R_{gs}^{HBD} be the HBD transmission rates of UAV-1 and GS, respectively, with the HBD sum rate defined as $R_{sum}^{HBD} = R_1^{HBD} + R_{gs}^{HBD}$. For HD mode, let R_1^{HD} and R_{gs}^{HD} be the HD transmission rate of UAV-1 and GS, respectively, with HD sum rate $R_{sum}^{HD} = R_1^{HD} + R_{gs}^{HD}$. To maintain a fair comparison between HBD and HD systems, let $R_i^{HBD} = \frac{1}{2}R_i^{HD}$ for $i \in \{1, gs\}$ [4]. The respective HBD and HD outage probabilities at GS and UAV-2 are defined in the following subsections.

A. Hybrid-Duplex Outage Probability at GS

In the proposed HBD-CNPC system, the FD-enabled GS concurrently receives $x_1[t]$ while transmitting $x_{gs}[t]$, resulting in strong SI. Let $X_1 = \Omega_X |h_{1,g}|^2$ be the instantaneous received signal power of the SOI at GS, which is modeled as a non-centered Chi-squared distributed RV with Rician K factor K_{X_1} . Similarly, let $Y_{si,1} = \Omega_X \alpha_{g,g} \gamma_\phi^2 |h_{si}|^2$ and $Y_{si,2} = \Omega_X \alpha_{g,g} \epsilon |h_{si}|^2$ be the instantaneous received signal power of the SI components. The RVs, $Y_{si,1}$ and $Y_{si,2}$, are independently modeled as a non-centered Chi-squared distributed RV with Rician K factor $K_{Y_{si,1}}$, and an exponentially distributed RV, respectively. The outage event at the FD-enabled GS is defined as $\mathcal{O}_{gs}^{HBD} = \{h_{1,g}, h_{si} : R_1^{HBD} \geq \log_2 \left(1 + \frac{X_1}{Y_{si,1} + Y_{si,2} + 1} \right)\}$, with the outage probability and the HBD threshold defined as $Pr(\mathcal{O}_{gs}^{HBD})$ and $\gamma_{th,gs}^{HBD} = 2^{R_1^{HBD}} - 1$, respectively. As Rician fading is assumed for both h_{si} and $h_{1,g}$, $Pr(\mathcal{O}_{gs}^{HBD})$ can be obtained from [4, eq. (6)].

B. Hybrid-Duplex Outage Probability at UAV-2

At UAV-2, inter-UAV interference from UAV-1 is experienced in the proposed HBD-CNPC system. Let $X_{gs} = \Omega_X \alpha_{g,2} |h_{g,2}|^2$ and $Y_1 = \Omega_X \alpha_{1,2} |h_{1,2}|^2$ be the instantaneous received signal power of the SOI and inter-UAV interference, respectively. The RVs, X_{gs} and Y_1 , are modeled as independent exponential and non-centered Chi-squared distributed RVs, respectively, with Rician K factor K_{Y_1} for Y_1 .

To manage inter-UAV interference at UAV-2, we consider two approaches in the present work. For the first approach, the Interference Ignorant (II) detector is assumed where interference ($x_1[t]$) at UAV-2 is ignored. For the second approach, the Successive Interference Cancellation (SIC) detector is assumed where interference ($x_1[t]$) is first detected and removed before the SOI ($x_{gs}[t]$) is detected [12].

1) *II Detector*: Let $O_2^{HBD(II)} = \{h_{g,2}, h_{1,2} : R_{gs}^{HBD} \geq \log_2 \left(1 + \frac{X_{gs}}{Y_{1+1}}\right)\}$ be the HBD outage event for the II detector. Then, substituting X_{gs} and Y_1 into [9, eq. (12)] yields the closed-form outage probability expression for the II detector ($Pr(O_2^{HBD(II)})$):

$$Pr(O_2^{HBD(II)}) \approx \sum_{n=0}^{K_{tr}} \sum_{l=0}^{n+1} \binom{n+1}{l} \times \alpha_{Ray}(n, \Omega_X \alpha_{g,2}, \gamma_{th,2}^{HBD}) E\{Y_1^l\}, \quad (12)$$

where $E\{Y_1^l\} = \Gamma(1+l) \left[\frac{\alpha_{1,2}}{1+K_{Y_1}}\right]^l {}_1F_1(-l, 1; -K_{Y_1})(\Omega_X)^l$ is the l^{th} moment of Y_1 [9, Table II] and ${}_1F_1(\bullet)$ represents the confluent Hypergeometric function [10].

2) *SIC Detector*: For the SIC detector, an outage event occurs when interference detection fails or when SOI detection fails after interference cancellation. Thus, the HBD outage event is defined as:

$$\begin{aligned} O_2^{HBD(SIC)} &= \left\{h_{g,2}, h_{1,2} : R_1^{HBD} > \log_2 \left(1 + \frac{Y_1}{1 + X_{gs}}\right)\right\} \\ &\cup \left\{h_{g,2}, h_{1,2} : R_1^{HBD} \leq \log_2 \left(1 + \frac{Y_1}{1 + X_{gs}}\right)\right. \\ &\quad \left., R_{gs}^{HBD} > \log_2(1 + X_{gs})\right\}. \end{aligned} \quad (13)$$

Theorem 1: The outage probability of the SIC detector at UAV-2 ($Pr(O_2^{HBD(SIC)})$) is:

$$\begin{aligned} Pr(O_2^{HBD(SIC)}) &\approx \sum_{n=0}^{K_{tr}} \sum_{l=0}^{n+1} \alpha_{Rice}(n, \Omega_X \alpha_{1,2}, K_{Y_1}, \gamma_{th,gs}^{HBD}) \binom{n+1}{l} E\{X_{gs}^l\} \\ &+ \sum_{n=0}^{K_{tr}} \alpha_{Ray}(n, \Omega_X \alpha_{g,2}, \gamma_{th,2}^{HBD}) \\ &- \sum_{n=0}^{K_{tr}} \sum_{i=0}^n \sum_{j=0}^{i+1} \alpha_{Rice}(i, \Omega_X \alpha_{1,2}, K_{Y_1}, \gamma_{th,gs}^{HBD}) (n-i+1) \binom{i+1}{j} \\ &\quad \times \alpha_{Ray}(n-i, \Omega_X \alpha_{g,2}, 1) \frac{(\gamma_{th,2}^{HBD})^{j+n-i+1}}{j+n-i+1}, \end{aligned} \quad (14)$$

where $E\{X_{gs}^l\} = \Gamma(1+l) (\Omega_X \alpha_{g,2})^l$ is the l^{th} moment of X_{gs} [9, Table II].

Proof: The proof can be found in Appendix A. ■

The outage probability expressions in (12) and (14) enable outage analysis for various inter-UAV interference scenarios, which is further discussed in Section V.

Fig. 4. Outage probability of the proposed HBD-CNPC system for $K_{tr} = 20$, $\alpha_{g,2} = 1$, and $K_{Y_1} = 15$.

C. Half-Duplex Outage Probability

Interference is non-existent at both GS and UAV-2 when operating in HD mode. Let the HD threshold at GS and UAV-2 be $\gamma_{th,gs}^{HD} = 2^{2R_{gs}^{HBD}} - 1$ and $\gamma_{th,2}^{HD} = 2^{2R_{gs}^{HBD}} - 1$, respectively. Then, the HD outage probability at GS ($Pr(O_{gs}^{HD})$) and UAV-2 ($Pr(O_2^{HD})$) are given as [9, Table I]:

$$Pr(O_{gs}^{HD}) \approx \sum_{n=0}^{K_{tr}} \alpha_{Rice}(n, \Omega_X \alpha_{1,g}, K_{X_1}, \gamma_{th,gs}^{HD}), \quad (15)$$

$$Pr(O_2^{HD}) \approx \sum_{n=0}^{K_{tr}} \alpha_{Ray}(n, \Omega_X \alpha_{g,2}, \gamma_{th,2}^{HD}). \quad (16)$$

The HD outage probability expressions in this section are used as benchmark comparison against HBD mode at GS and UAV-2, which is discussed in Section V.

V. NUMERICAL RESULTS

In this section, numerical results of the outage probability at both the FD-enabled GS and UAV-2 are presented. Monte Carlo simulations with 10^7 samples have also been conducted. We let $R_{sum}^{HD} = R_{sum}^{HBD} = 0.15$ to maintain a fair comparison between the HBD and HD systems, with $\sigma_g^2 = \sigma_2^2 = -115\text{dBm}$ and $f_c = 968\text{ MHz}$ (L-band) [13].

The outage probability of the HBD-CNPC system is shown in Fig. 4. In particular, the HBD outage probability at UAV-2 for the II and SIC detectors, i.e., $Pr(O_2^{HBD(II)})$ and $Pr(O_2^{HBD(SIC)})$, are obtained from (12) and (14), respectively. The HBD outage probability at GS ($Pr(O_{gs}^{HBD})$) is computed from [4, eq. (6)]. Similarly, the HD outage probability at UAV-2 and GS is obtained from (15) and (16), respectively.

Observation 1: The outage probability of the SIC detector decreases as inter-UAV interference increases. In contrast, an error floor is encountered by the II detector, even as inter-UAV interference reduces.

Fig. 5. Transmission power requirement (dBm) at GS to maintain $Pr(O_2^{HBD(SIC)}) \leq 10^{-3}$ and $Pr(O_2^{HD}) \leq 10^{-3}$ for $\alpha_{g,2} = 1$, $\alpha_{1,2} \in \{1, 1.5\}$ and $K_{Y1} = 15$.

From Fig. 4, it is observed that the SIC detector achieves lower outage probability than the II detector. When the SOI ($x_{gs}[t]$) and the interfering signal ($y_1[t]$) experience Rayleigh and Rician fading, respectively, inter-UAV interference can be detected and removed easily. Therefore, $x_{gs}[t]$ can be reliably detected by the SIC detector. It is also observed that higher inter-UAV interference levels, e.g., $\alpha_{1,2} = 1.5$, result in lower outage probability for the SIC detector at high Ω_X , with $y_1[t]$ being more likely to be detected successfully. For the II detector, it is evident that lower inter-UAV interference levels, e.g., $\alpha_{1,2} = 0.5$, result in lower outage probability for the II detector. However, the II detector is not as effective as the SIC detector, even when inter-UAV interference is reduced (e.g., $\alpha_{1,2} = 0.5$), particularly at high SNR where an error floor can be observed. Since only the interfering signal experiences Rician fading, the detection of $x_{gs}[t]$ is less reliable due to Rayleigh fading on the desired link ($h_{g,2}$).

When compared against HD-CNPC systems, the SIC detector attains lower outage probability, even at high Ω_X . In contrast, the II detector attains lower outage probability than HD-CNPC systems at only low Ω_X . Also, it can be seen from Fig. 4 that when operating in HBD mode, the GS experiences lower outage probability than UAV-2 for $0dB \leq \Omega_X \leq 30dB$ and $\alpha_{1,2} \in \{0.5, 1, 1.5\}$. Similar observations are also made when both GS and UAV-2 are operating in HD mode due to severe fading on $h_{g,2}$. Thus, the performance bottleneck is at UAV-2 for both HBD-CNPC and HD-CNPC systems. Therefore, overcoming the effects of fading and inter-UAV interference, which can be encountered in urban environments, are critical to the implementation of HBD-CNPC systems.

Observation 2: The SIC detector enables longer transmission ranges and lower transmission power requirements for the HBD-CNPC system.

Based on Fig. 4, the GS transmission power (P_t) is com-

Fig. 6. Impact of Rician K factor on outage probability at UAV-2 for $K_{tr} = 20$, $\alpha_{g,2} = 1$, and $\Omega_X = 10dB$.

puted from (2) and plotted in Fig. 5 for the HBD-CNPC and HD-CNPC systems. In particular, the transmission power at GS is computed to maintain $Pr(O_2^{HBD(SIC)}) \leq 10^{-3}$ and $Pr(O_2^{HD}) \leq 10^{-3}$. The II detector is not considered in Fig. 5 as it exhibits an error floor in Fig. 4. From Fig. 5, it can be seen that employing the SIC detector enables additional transmission ranges of up to 3 Km compared to the HD-CNPC systems. Also, the SIC detector enables the proposed HBD-CNPC system to maintain a specific outage probability level, e.g., $Pr(O_2^{HBD(SIC)}) \leq 10^{-3}$, with lower transmission power requirements. Therefore, the HBD-CNPC system can potentially reduce the size, weight and power requirements of UAVs as compared to HD-CNPC systems.

Observation 3: Changes to the Rician K factor only affects the SIC detector.

The impact of the interfering link's ($h_{1,2}$) Rician K factor, i.e., K_{Y1} , on the outage probability at UAV-2 is plotted in Fig. 6 for the II and the SIC detectors. As inter-UAV interference is ignored by the II detector, $Pr(O_2^{HBD(II)})$ is unaffected as K_{Y1} varies. In contrast, changes to the outage probability of the SIC detector can be observed in Fig. 6 when K_{Y1} increases. As larger values of K_{Y1} corresponds to stronger line-of-sight components for the inter-UAV interference ($y_1[t]$), increasing K_{Y1} improves the likelihood of successfully detecting and removing $y_1[t]$ for the SIC detector. Thus, to further improve the reliability of the SIC detector, relaying strategies, e.g., interference forwarding, can be considered especially when support for large numbers of UAVs is needed.

The analysis presented in this section demonstrates the superior reliability and transmission range of the proposed HBD-CNPC system over existing HD-CNPC systems. To meet higher Quality-of-Service requirements, advance interference management strategies, relaying strategies, and optimal power allocation strategies can be considered to overcome the effects of inter-UAV interference and fading in UAV communications.

To this end, the design of relaying strategies and transmit power optimization at UAV-1 and GS are beyond the scope of the current work and are left as future extension of this work.

VI. CONCLUSION

To address spectrum scarcity in UAV communications, a HBD-CNPC system consisting of HD UAVs and FD GSs is proposed. Alternative representations for the statistics of both the Rician fading and the Rayleigh fading channels are presented, with closed-form outage probability expressions derived for the HBD-CNPC and HD-CNPC systems. Outage analysis shows that the SIC detector outperforms the II detector when the SOI experiences fading that is more severe than the interfering signal. We also show that for better reliability, longer transmission range, and lower transmission power requirements can be achieved by the proposed HBD-CNPC system. Future extension of this Work pertaining to the design of advance interference management strategies, relaying strategies, and optimal power allocation strategies can be considered to overcome effects of inter-UAV interference and fading for HBD-CNPC systems.

APPENDIX A PROOF OF THEOREM 1

From (13), the outage probability of the SIC detector at UAV-2 ($Pr(O_2^{HBD(SIC)})$) can be expressed as:

$$Pr(O_2^{HBD(SIC)}) = E_{X_{gs}} \{F_{Y_1}(\gamma_{th,gs}^{HBD}(1 + X_{gs}))\} + F_{X_{gs}}(\gamma_{th,2}^{HBD}) - \int_0^{\gamma_{th,2}^{HBD}} F_{Y_1}(\gamma_{th,gs}^{HBD}(1 + x))f_{X_{gs}}(x)dx, \quad (17)$$

where $f_{X_{gs}}(x)$ is the PDF of X_{gs} , $F_{Y_1}(\bullet)$ and $F_{X_{gs}}(\bullet)$ are the CDF of Y_1 and X_{gs} , respectively. Also, $E_X\{\bullet\}$ is the expectation function taken with respect to the RV X .

The CDF of X_{gs} , i.e., $F_{X_{gs}}(\gamma_{th,2}^{HBD})$ can be obtained from (11) as:

$$\sum_{n=0}^{K_{tr}} \alpha_{Ray}(n, \Omega_X \alpha_{g,2}, \gamma_{th,2}^{HBD}). \quad (18)$$

To evaluate the integral in (17), we first let $c(n)$ and $d(n)$ represent the series expansion of an arbitrary CDF and PDF, respectively. From [9, eq. (10)], (10) and (7), let $c(n) = \sum_{j=0}^{n+1} \alpha_{Rice}(n, \Omega_X \alpha_{1,2}, K_{Y_1}, \gamma_{th,gs}^{HBD}) \binom{n+1}{j} x^j$ and $d(n) = \alpha_{Ray}(n, \Omega_X \alpha_{g,2}, 1)(n+1)x^n$. Thus, $F_{Y_1}(\gamma_{th,gs}^{HBD}(1 + x))$ and $f_{X_{gs}}(x)$ can be expressed as:

$$F_{Y_1}(\gamma_{th,gs}^{HBD}(1 + x)) \approx \sum_{n=0}^{tr} \sum_{j=0}^{n+1} \binom{n+1}{j} \times \alpha_{Rice}(n, \Omega_X \alpha_{1,2}, K_{Y_1}, \gamma_{th,gs}^{HBD}) x^j \quad (19)$$

$$f_{X_{gs}}(x) \approx \sum_{n=0}^{tr} \alpha_{Ray}(n, \Omega_X \alpha_{g,2}, 1)(n+1)x^n. \quad (20)$$

Thereafter, applying the Cauchy product theorem [11], [14] and interchanging the integration and summation yields:

$$\begin{aligned} & \int_0^{\gamma_{th,2}^{HBD}} F_{Y_1}(\gamma_{th,gs}^{HBD}(1 + x))f_{X_{gs}}(x)dx \\ & \approx \sum_{n=0}^{K_{tr}} \sum_{i=0}^n \int_0^{\gamma_{th,2}^{HBD}} c(i)d(n-i)dx \\ & \approx \sum_{n=0}^{K_{tr}} \sum_{i=0}^n \sum_{j=0}^{i+1} \alpha_{Rice}(i, \Omega_X \alpha_{1,2}, K_{Y_1}, \gamma_{th,gs}^{HBD})(n-i+1) \binom{i+1}{j} \\ & \quad \times \alpha_{Ray}(n-i, \Omega_X \alpha_{g,2}, 1) \frac{(\gamma_{th,2}^{HBD})^{j+n-i+1}}{j+n-i+1} \end{aligned} \quad (21)$$

Also, $E_{X_{gs}}\{F_{Y_1}(\gamma_{th,gs}^{HBD}(1 + X_{gs}))\}$ can be obtained from [9, eq. (8)] and (7) as:

$$\begin{aligned} & E_{X_{gs}}\{F_{Y_1}(\gamma_{th,gs}^{HBD}(1 + X_{gs}))\} \\ & \approx \sum_{n=0}^{K_{tr}} \sum_{l=0}^{n+1} \alpha_{Rice}(n, \Omega_X \alpha_{1,2}, K_{Y_1}, \gamma_{th,gs}^{HBD}) \binom{n+1}{l} E\{X_{gs}^l\}, \end{aligned} \quad (22)$$

where $E\{X_{gs}^l\}$ is the l^{th} moment of X_{gs} . Combining (18), (21), and (22) yields (14), which completes the proof.

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