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2019

Tan, E. Z. H., Madhukumar, A. S., Sirigina, R. P. & Krishna, A. K. (2018). Hybrid-duplex systems for UAV communications under Rician shadowed fading. Proceedings of 2018 IEEE 88th Vehicular Technology Conference (VTC-Fall). doi:10.1109/VTCFall.2018.8690623

<https://hdl.handle.net/10356/144698>

<https://doi.org/10.1109/VTCFall.2018.8690623>

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Hybrid-Duplex Systems for UAV Communications under Rician Shadowed Fading

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Abstract—With the growing popularity of unmanned aerial vehicles (UAVs), spectrum management is a pressing issue, particularly for multi-UAV systems. To this end, a hybrid-duplex (HBD) UAV communication system (UCS) consisting of a full-duplex (FD) enabled ground station (GS), and legacy half-duplex (HD) UAVs is proposed in this paper. To model the fading and shadowing environment commonly encountered in UAV communications, a mix of Rician and Rician shadowed fading is assumed. In particular, novel power series approximations of the Rician shadowed fading power probability density function (PDF), and cumulative distribution function (CDF) are presented, along with closed-form outage probability expressions. Performance analysis shows that the proposed HBD-UCS exhibits lower outage probability than the HD-UCS when shadowing is encountered at low signal-to-noise ratios (SNRs). Also, inter-UAV interference has a stronger influence on outage probability decay at low SNR regimes, with lower inter-UAV interference corresponding to a sharper decline in outage probability.

Index Terms—Unmanned Aerial Vehicle, Spectrum Efficiency, Full-Duplex and Hybrid-Duplex systems, Outage Probability, Rician and Shadowed Rician fading, $\kappa - \mu$ Shadowed Fading.

I. INTRODUCTION

The deployment of systems with multiple small, low altitude unmanned aerial vehicles (UAVs) for a multitude of applications is rapidly gaining traction [1]. Having multiple cooperative UAVs enables multi-UAV systems to provide high-speed communications in applications as diverse as infrastructure inspection and telecommunications relaying [1]. However, the lack of available spectrum is one of the main impediment to multi-UAV systems, especially when the accommodation of large numbers of UAVs on a common spectrum is required [2].

To this end, a hybrid-duplex (HBD) UAV communication system (UCS) with half-duplex (HD) UAVs and full-duplex (FD) ground stations (GSs) is proposed as a potential solution towards efficient spectrum utilization. In HBD systems, HD and FD nodes communicate simultaneously on the same spectrum. Thus, inter-node interference and self-interference (SI) are encountered at the HD and FD nodes, respectively [3]. Nonetheless, the HBD paradigm has been applied in related areas, such as in aeronautical communication systems [3].

As the proposed HBD-UCS is a multi-UAV system, fading and shadowing can occur [4], especially in urban environments

[5]. Specifically, line-of-sight (LOS) blockage, i.e., Rician shadowed fading, has been observed in empirical data [6]. Although the effect of shadowing on UAV communications has been studied in the literature, Rician shadowed fading, which is also encountered in land mobile satellite channels [7], is an area that has not been extensively studied for UAV communications.

Rician shadowed fading can be modeled using a mixture of non-centered Chi-squared and Nakagami-m distributions for the multipath and LOS components, respectively [8], [9]. To achieve such a distribution, the $\kappa - \mu$ shadowed fading model was proposed by Paris [8]. In particular, Paris [8] showed that the $\kappa - \mu$ shadowed fading distribution can be used to obtain the one-sided Gaussian, Rayleigh, $\kappa - \mu$, Rician, and Rician shadowed fading distributions by substituting appropriate values into the shaping parameters.

Although the statistics of the $\kappa - \mu$ shadowed fading model have been presented in [8] and [9], the associated statistics for Rician shadowed fading can be complicated thus making performance metrics, e.g., outage probability, difficult to compute. In this aspect, the major contributions in this paper are as follows.

- Novel power series approximations of the Rician shadowed fading power probability density function (PDF) and cumulative distribution function (CDF) are derived from the $\kappa - \mu$ shadowed fading distribution.
- Closed-form outage probability expressions of the HBD-UCS and HD-UCS under Rician shadowed fading are presented using the approximated Rician shadowed fading power PDF. Using the closed-form outage probability expressions, the performance analysis of the HBD-UCS is conducted where the effect of shadowing is demonstrated.

The organization of this paper is as follows. The system model is introduced in Section II, with the Rician shadowed fading power PDF and CDF expressions 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

Fig. 1 depicts the proposed HBD-UCS for unmanned aerial vehicle (UAV) communications in a suburban environment.

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).

In particular, the scenario in Fig. 1 involves two HD UAVs and a FD-enabled ground station (GS) communicating on the same spectrum, e.g., 3G/LTE [1]. Evidently, interference is unavoidable in the proposed HBD-UCS. At Unmanned Aerial Vehicle 1 (UAV-1), signals are transmitted to both GS and Unmanned Aerial Vehicle 2 (UAV-2), while the FD-enabled GS simultaneously transmits signals to UAV-2. Therefore, self-interference (SI) and inter-UAV interference are experienced at the FD-enabled GS and UAV-2, respectively.

It should be noted that a mix of Rician fading [2] and Rician shadowed fading [9] is assumed to adequately model the suburban UAV communications channels, due to the likely obstruction of the line-of-sight (LOS) component by buildings [4], [5] as a result of altitude restrictions. Also, the Doppler effect is assumed to be compensated in this work.

At the GS, let $x_1[t]$ be the signal-of-interest (SOI) transmitted from UAV-1, and $x_{si}[t]$ be the SI, where $x_{si}[t] = x_{gs}[t]$ and $x_{gs}[t]$ is the transmitted signal from the GS. Also, let the channel between UAV-1 and GS be $h_{1,g}[t]$, the SI channel gain be h_{si} , and the SI channel gain estimate error be $\tilde{h}_{si} = h_{si} - \hat{h}_{si}$, where $\hat{h}_{si}$ is the imperfect estimation of the SI channel gain, and Rician fading is assumed for both h_{si} and $h_{1,g}$. Then, the received signal at GS can be written as [10]:

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

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 [10]. 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 [11].

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

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

where P_t , $d_{1,g}$, f_c and n are the transmit power (Watts), distance (Km), carrier frequency (MHz) and pathloss exponent,

respectively. In this work, $h_{1,g}[t]$ is chosen as the reference link. Hence, the average received signal power in the other links are expressed relative to $h_{1,g}[t]$ via the multiplicative factor $\alpha_{i,j}$ as:

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

At UAV-2, let $x_{gs}[t]$ be the SOI transmitted from GS and $x_1[t]$ be the inter-UAV interference from UAV-1. Also, let $h_{g,2}[t]$ and $h_{1,2}[t]$ be the Rician shadowed fading channels between GS and UAV-2, and UAV-1 and UAV-2, respectively. Then, the received signal at UAV-2 can be expressed as:

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

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 both the FD-enabled GS and UAV-2, the interference ignorant (II) interference management approach is considered in this work.

III. RICIAN SHADOWED FADING DISTRIBUTION

For a Rician shadowed fading channel h , the probability density function (PDF) can be obtained using the $\kappa - \mu$ shadowed fading distribution [9]. Specifically, the $\kappa - \mu$ shadowed fading distribution has κ , μ and m as shaping parameters, representing the ratio between the total powers of the dominant component to the scattered component, number of multipath clusters, and the severity of shadowing through Nakagami- m distribution [9]. Setting $\mu = 1$ and letting κ be the Rician K factor, i.e., $\kappa = K$, yields the Rician shadowed fading power PDF [9, Table I]:

$$f_h(x) = \frac{m^m (1+K)}{\Omega (K+m)^m} \exp\left(-\frac{(1+K)x}{\Omega}\right) {}_1F_1\left(m; 1; \frac{K(1+K)x}{(K+m)\Omega}\right), \quad (5)$$

where Ω and ${}_1F_1(\bullet)$ are the average received power and the confluent Hypergeometric function [12], respectively.

From [13], ${}_1F_1(a; b; z) = \sum_{k \geq 0} \frac{(a)_k z^k}{(b)_k k!}$, where $(a)_k = \frac{\Gamma(a+k)}{\Gamma(a)}$ is the Pochhammer symbol [9]. Since $\frac{(a)_{k+1}}{(a)_k} = a+k$ [14], and $\Gamma(k+a) \approx k^a \Gamma(k)$ when $k \rightarrow \infty$ [15, eq. (25)], ${}_1F_1(a; 1; z) = \sum_{k \geq 0} f(k)$, where $f(k) = \frac{(a)_k}{\Gamma^2(k+1)} z^k$. The absolute convergence of $\sum_{k \geq 0} f(k)$ is easily proven via the D'Alembert test:

$$\lim_{k \rightarrow \infty} \frac{f(k+1)}{f(k)} = \lim_{k \rightarrow \infty} \frac{(a+k)z}{k^2} = 0. \quad (6)$$

Let $c(n) = \frac{m^m (1+K)}{\Omega (K+m)^m} \frac{(m)_n}{\Gamma^2(n+1)} \left(\frac{K(1+K)}{(K+m)\Omega}\right)^n x^n$ and $d(i) = \left(\frac{-(1+K)}{\Omega}\right)^i \frac{x^i}{i!}$. Using the Cauchy product theorem, (5) can be expressed in truncated form as:

$$\begin{aligned} f_h(x) &= \left(\sum_{n \geq 0} c(n)\right) \left(\sum_{i \geq 0} d(i)\right) \\ &\approx \sum_{n=0}^{K_{tr}} \sum_{i=0}^n \frac{m^m (1+K)}{\Omega (K+m)^m} \frac{(m)_i}{\Gamma^2(i+1)} \left(\frac{K(1+K)}{(K+m)\Omega}\right)^i \\ &\quad \times \left(\frac{-(1+K)}{\Omega}\right)^{n-i} \frac{x^n}{(n-i)!}, \end{aligned} \quad (7)$$

Fig. 2. Comparison between the exact PDF and power series approximation equivalent for $\Omega = 1$ and $K_{tr} = 50$.

where K_{tr} denotes the truncation order.

The power series approximation of the Rician shadowed fading power PDF, given in (7), is shown in Fig. 2. For comparison, the exact PDF in (5) is also plotted. Evidently, (7) provides a close approximation to the exact PDF. In fact, although not shown in Fig. 2, the Rician fading power PDF can be obtained by setting $m = \infty$. However, the downside of (7) is the computation time due to the Pochhammer symbol, which increases as $m \rightarrow \infty$.

Continuing from (7), the cumulative distribution function (CDF) of h can also be expressed as a power series:

$$F_h(\gamma) = \int_0^\gamma f_h(x) dx \approx \sum_{n=0}^{K_{tr}} \sum_{i=0}^n (-1)^{n-i} \left(\frac{m}{K+m} \right)^m \frac{(m)_i}{\Gamma^2(i+1)} \times \left(\frac{K}{K+m} \right)^i \left(\frac{1+K}{\Omega} \right)^{n+1} \frac{\gamma^{n+1}}{(n-i)!(n+1)}. \quad (8)$$

The l^{th} moment of h is given in [9, eq. (10)] as $E\{h^l\} = \left(\frac{\Omega}{1+K} \right)^l \Gamma(1+l) \left(\frac{m}{K+m} \right)^{m-1-l} {}_2F_1\left(1-m, 1+l; 1; \frac{-K}{m}\right)$, where ${}_2F_1(\bullet)$ is the Gauss hypergeometric function [9]. Together, the closed-form expressions of the PDF, CDF and fractional moments of h presented in this section are essential in evaluating the outage probability of the proposed HBD-UCS, which is discussed in Section IV.

IV. OUTAGE PROBABILITY DERIVATIONS

The outage probability of the proposed HBD-UCS is derived in this section. Let the HBD transmission rates of UAV-1 and GS be R_1^{HBD} and R_{gs}^{HBD} , respectively, and the sum rate of the HBD system be $R_{sum}^{HBD} = R_1^{HBD} + R_{gs}^{HBD}$. The HD transmission rates of UAV-1 and GS are similarly defined as R_1^{HD} and R_{gs}^{HD} , respectively, with the sum rate of the HD system defined as $R_{sum}^{HD} = R_1^{HD} + R_{gs}^{HD}$. Also, let $R_i^{HBD} = \frac{1}{2} R_i^{HD}$ for $i \in \{1, gs\}$

for fair comparison between HBD and HD systems [3]. The respective HBD and HD outage probabilities at GS and UAV-2 are defined in the following subsections.

A. Hybrid-Duplex Outage Probability

At the FD-enabled GS, $x_1[t]$ is received while $x_{gs}[t]$ is simultaneously transmitted, resulting in strong SI at GS. Let the instantaneous received signal power of the SOI at GS be $X_1 = \Omega_X |h_{1,g}|^2$, modeled as a non-centered Chi-squared distributed RV with Rician K factor K_{X_1} . Also, Let the instantaneous received signal power of the SI components be $Y_{si,1} = \Omega_X \alpha_{g,g} \gamma_\phi^2 |h_{si}|^2$ and $Y_{si,2} = \Omega_X \alpha_{g,g} |\tilde{h}_{si}|^2$. The former ($Y_{si,1}$) and latter ($Y_{si,2}$) are modeled as a non-centered Chi-squared distributed RV with Rician K factor $K_{Y_{si,1}}$, and an exponentially distributed RV, respectively. Let O_{gs}^{HBD} , $Pr(O_{gs}^{HBD})$, and $\gamma_{th,gs}^{HBD} = 2^{R_1^{HBD}} - 1$, be the outage event, outage probability, and the HBD threshold at the FD-enabled GS, respectively. Since Rician fading is assumed for both h_{si} and $h_{1,g}$, $Pr(O_{gs}^{HBD})$ is computed using the closed-form outage expression in [3, eq. (6)].

At UAV-2, let the instantaneous received signal power of the SOI and interference be $X_{gs} = \Omega_X \alpha_{g,2} |h_{g,2}|^2$ and $Y_1 = \Omega_X \alpha_{1,2} |h_{1,2}|^2$, respectively. Both X_{gs} and Y_1 are respectively modeled as independent Rician shadowed distributed RVs, with Rician K factors $K_{X_{gs}}$ and K_{Y_1} , and shadowing severity parameters $m_{X_{gs}}$ and m_{Y_1} . Moreover, let $\gamma_{th,2}^{HBD} = 2^{R_{gs}^{HBD}} - 1$ be the HBD threshold and $O_2^{HBD(II)} = \{h_{g,2}, h_{1,2} : R_{gs}^{HBD} \geq \log_2 \left(1 + \frac{X_{gs}}{Y_1 + 1} \right)\}$ be the HBD outage event. Then from [15, eq. (8)], the closed-form outage probability expression at UAV-2 is:

$$\begin{aligned} Pr(O_2^{HBD(II)}) &= E_{Y_1} \left\{ F_{X_{gs}} \left(\gamma_{th,2}^{HBD} (1 + Y_1) \right) \right\} \\ &\approx \sum_{n=0}^{K_{tr}} \sum_{i=0}^n \sum_{j=0}^{n+1} (-1)^{n-i} \left(\frac{m_{X_{gs}}}{K_{X_{gs}} + m_{X_{gs}}} \right)^{m_{X_{gs}}} \frac{(m_{X_{gs}})_i}{\Gamma^2(i+1)} \\ &\quad \times \left(\frac{K_{X_{gs}}}{K_{X_{gs}} + m_{X_{gs}}} \right)^i \frac{\left(\gamma_{th,2}^{HBD} (1 + K_{X_{gs}}) \right)^{n+1}}{(n-i)!(n+1)} \binom{n+1}{j} \\ &\quad \times \left(\frac{\alpha_{1,2}}{1 + K_{Y_1}} \right)^j \Gamma(1+j) \left(\frac{m_{Y_1}}{K_{Y_1} + m_{Y_1}} \right)^{m_{Y_1}-1-j} \\ &\quad \times {}_2F_1 \left(1 - m_{Y_1}, 1 + j; 1; \frac{-K_{Y_1}}{m_{Y_1}} \right) (\Omega_X)^{j-n-1}, \end{aligned} \quad (9)$$

where $E_{Y_1}\{\bullet\}$ is the statistical expectation taken with respect to the PDF of Y_1 and $F_{X_{gs}}(\bullet)$ is the CDF of X_{gs} .

B. Half-Duplex Outage Probability

In HD mode, no interference is experienced at both GS and UAV-2. Let $\gamma_{th,gs}^{HD} = 2^{R_1^{HD}} - 1$ and $\gamma_{th,2}^{HD} = 2^{R_{gs}^{HD}} - 1$ be the HD threshold at GS and UAV-2, respectively. Then, the HD outage probability at GS ($Pr(O_{gs}^{HD})$) can be computed from

Fig. 3. Outage probability at UAV-2 for $K_{tr} = 20$, $\alpha_{g,2} = 1$, $K_{X_{gs}} = K_{Y_1} = 15$, and $m_{Y_1} = 10$.

TABLE I
SUMMARY OF HBD PERFORMANCE AT UAV-2

$\alpha_{1,2}$	$m_{X_{gs}}$	$Pr(O_2^{HBD(II)}) < Pr(O_2^{HD})$	Δ_1	Δ_2
0	5	$0dB \leq \Omega_X \leq 30dB$	7dB	10.5dB
0	15	$0dB \leq \Omega_X \leq 30dB$	3dB	7dB
0.1	5	$\Omega_X \leq 10dB$	9dB	12dB
0.1	15	$\Omega_X \leq 10dB$	6.5dB	8dB

[3, eq. (12)]. At UAV-2, the HD outage probability is obtained from (8) as:

$$Pr(O_2^{HD}) \approx \sum_{n=0}^{K_{tr}} \sum_{i=0}^n (-1)^{n-i} \left(\frac{m_{X_{gs}}}{K_{X_{gs}} + m_{X_{gs}}} \right)^{m_{X_{gs}}} \frac{(m_{X_{gs}})_i}{\Gamma^2(i+1)} \left(\frac{K_{X_{gs}}}{K_{X_{gs}} + m_{X_{gs}}} \right)^i \left(\frac{1 + K_{X_{gs}}}{\alpha_{g,2} \Omega_X} \right)^{n+1} \frac{(\gamma_{th,2}^{HD})^{n+1}}{(n-i)!(n+1)}. \quad (10)$$

The HD outage probability expressions 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, the numerical results pertaining to the outage probability at UAV-2 are presented. Monte Carlo simulations with 10^{11} samples have also been conducted. For fair comparison between the HBD and HD systems, we let $R_{sum}^{HD} = R_{sum}^{HBD} = 1$, with $\sigma_g^2 = \sigma_2^2 = -115dBm$.

The outage probability at UAV-2 is shown in Fig. 3. In particular, the HBD and HD Rician shadowed fading outage probability at UAV-2, i.e., $Pr(O_2^{HBD(II)})$ and $Pr(O_2^{HD})$, are obtained from (9) and (10), respectively. For outage probability comparison in the absence of shadowing, the HBD and HD Rician fading outage probability at UAV-2, i.e., no shadowing on $h_{1,2}$ and $h_{g,2}$, are computed from [3, eq. (8)] and [3, eq. (13)], respectively, and plotted in Fig. 3.

Table I shows a summary of the HBD performance at UAV-2 obtained from Fig. 3. Taking $Pr(O_2^{HBD(II)})$ at $\Omega_X = 15dB$

to be the benchmark, we define Δ_1 and Δ_2 as fade margin parameters. For Δ_1 , comparison is between the HBD-UCS and the HD-UCS without shadowing while for Δ_2 , comparison is between the HBD-UCS and the HBD-UCS without shadowing at equivalent inter-UAV interference levels.

When $m_{X_{gs}}$ is small, e.g., $m_{X_{gs}} = 5$, severe shadowing is encountered at UAV-2 [9]. Under such scenarios, it can be seen from Fig. 3 that $Pr(O_2^{HBD(II)}) < Pr(O_2^{HD})$ when $\Omega_X \leq 10dB$ since the HD mode requires a higher threshold than the HBD mode. However, $Pr(O_2^{HBD(II)}) \geq Pr(O_2^{HD})$ when $\Omega_X > 10dB$. As Ω_X increases, inter-UAV interference at UAV-2 is much stronger than the receiver noise. In contrast, operating in HD mode causes inter-UAV interference to be non-existent at UAV-2. Hence, only the HBD UAV-2 becomes interference limited and an error floor is present in $Pr(O_2^{HBD(II)})$. Similar observations are also made when light shadowing is encountered at UAV-2, e.g., $m_{X_{gs}} = 15$, albeit with lower $Pr(O_2^{HBD(II)})$. In fact, Kumar and Kalyani [16] noted that as $m \rightarrow \infty$, $\kappa - \mu$ shadowed fading outage probability curve approaches that of $\kappa - \mu$ fading. In the context of the system model in Fig. 1, Fig. 3 indicates that $Pr(O_2^{HBD(II)})$ is lower as $\frac{m_{X_{gs}}}{m_{Y_1}} \rightarrow \infty$ and vice-versa. As a large m results in $\kappa - \mu$ fading, $m_{X_{gs}} \rightarrow \infty$ results in Rician fading which is a special case of $\kappa - \mu$ fading [8].

It can also be seen from Fig. 3 that the shadowing parameter $m_{X_{gs}}$ does not affect Ω_X for which the crossover point for the outage probabilities occur, i.e., $Pr(O_2^{HBD(II)}) < Pr(O_2^{HD})$ when $\Omega_X \leq 10dB$ for $m_{X_{gs}} \in \{5, 15, \infty\}$. Instead, the outage probability range in which these crossover points occur changes with increasing $m_{X_{gs}}$. For instance, the crossover occurs between the range of 10^{-2} and 10^{-3} when $m_{X_{gs}} = 5$. For $m_{X_{gs}} = 15$, the crossover occurs between the range of 10^{-3} and 10^{-4} . Thus, shadowing can have a considerable impact on outage probability decay rate. Apart from affecting the decay rate of outage probability, Table I shows that the presence of shadowing necessitates higher transmission powers to maintain a desired level of reliability. In particular, Δ_1 and Δ_2 indicates that the proposed HBD-UCS requires higher transmission power to maintain the same level of outage probability as that of HD-UCS and HBD-UCS without shadowing.

Nevertheless, the trends in Fig. 3 highlights the robustness of the proposed HBD-UCS when shadowing is experienced. From Fig. 3, it is evident that HD-UCS is less reliable than HBD-UCS at low SNR regimes in the presence of shadowing. Even under severe shadowing scenarios, the proposed HBD-UCS achieves lower outage probability than HD-UCS. Thus, the proposed HBD-UCS offers superior reliability over HD-UCS when operating at low SNR regimes in urban environments.

Fig. 4 shows the outage probability comparison between UAV-2 and the GS. In particular, $Pr(O_2^{HBD(II)})$ and $Pr(O_2^{HBD})$ are plotted for HBD mode while $Pr(O_2^{HD})$ and $Pr(O_2^{HD})$ are plotted for HD mode. It can be seen from Fig. 4 that $Pr(O_2^{HBD(II)})$ exhibits a steeper drop when $\alpha_{1,2} = 0.1$ than when $\alpha_{1,2} = 0.5$ at low Ω_X , e.g., $\Omega_X \leq 5dB$. At low Ω_X

Fig. 4. Comparison of outage probability at UAV-2 and GS for $K_{tr} = 20$, $\alpha_{g,2} = 1$, $K_{X1} = K_{Xgs} = K_{Y1} = K_{Ysi,1} = 15$, $m_{Y1} = 10$, $\gamma_\phi^2 = -130\text{dBm}$, and $\epsilon = 0.01$.

regimes, the combined effect of the receiver noise and inter-UAV interference at UAV-2 greatly influences $Pr(O_2^{HBD(II)})$, affecting outage probability decay rates, especially when inter-UAV interference level ($\alpha_{1,2}$) is high. The decrease in outage probability decay rate in the presence of light shadowing, e.g., $m_{Xgs} = 15$ is evident in Fig 4, where $Pr(O_2^{HBD(II)}) \geq Pr(O_2^{HBD})$ when $\Omega_X \geq 4\text{dB}$ and $\alpha_{1,2} = 0.5$. When $\alpha_{1,2} = 0.1$, $Pr(O_2^{HBD(II)}) \geq Pr(O_2^{HBD})$ when $\Omega_X \geq 11\text{dB}$. Therefore, in contrast to [16], [17] where noise was ignored, Fig 4 shows that noise must also be considered, especially in UAV communications where inter-UAV interference can be weak.

It is also evident from Fig. 4 that the bottleneck of outage probability performance in a HBD-UCS are on the links with Rician shadowed fading since $Pr(O_2^{HBD(II)}) > Pr(O_{gs}^{HBD})$ and $Pr(O_2^{HBD}) \geq Pr(O_{gs}^{HBD})$. Although the proposed HBD-UCS exhibits superior reliability over HD-UCS in the presence of inter-UAV interference and shadowing, the performance bottleneck must be mitigated to support higher Quality-of-Service requirements. Solutions involving advance interference management strategies, along with optimal power allocation strategies, can be explored to overcome shadowing effects in UAV communications. The design of advanced interference resilient decoding schemes and the optimization of the transmit powers at UAV-1 and GS are beyond the scope of the current work and are left for a future extension of this work.

VI. CONCLUSION

To improve spectrum utilization in UAV communications, an HBD-UCS consisting of HD UAVs and FD GSs is proposed. A mix of Rician and Rician shadowed fading is assumed for the UAV communication links to account for the fading and shadowing environment in UAV communications. To this end, power series approximations of the Rician shadowed fading power PDF and CDF are derived. From the derived expressions, closed-form outage probability expressions

for the HBD-UCS and HD-UCS are also presented. Analysis revealed that at low SNR regimes, the proposed HBD-UCS exhibits superior reliability than the HD-UCS in a shadowing environment and that low inter-UAV interference increases the outage probability decay rate of the HBD-UCS. Work is in progress on designing advanced interference resilient decoding schemes and transmit power optimization for the HBD-UCS.

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