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On the Performance Analysis of Hybrid-Duplex Systems for Aeronautical Communications

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Abstract—Air traffic growth is expected to rise sharply in the near future, causing a swell in data communication demands on the congested aeronautical spectrum which cannot be met with existing aeronautical communication systems. To this end, a hybrid-duplex (HBD) aeronautical communications system consisting of a full-duplex (FD) enabled ground station, and legacy half-duplex (HD) air-stations is proposed as a direct solution to boost spectral efficiency. In particular, the system level outage probabilities and transmission power requirements of the proposed HBD and HD aeronautical communication systems are analyzed. Performance analysis shows that the proposed HBD system can attain better outage performance in the en route scenario. The proposed HBD system is also able to support an equivalent data rate as an HD system with lower transmit power and signal-to-interference-plus-noise-ratio (SINR) requirements and longer transmission range when inter-aircraft interference and residual self-interference is kept sufficiently low.

Index Terms—Aeronautical Communications, Spectral Efficiency, Full-Duplex, Hybrid-Duplex, Outage Probability, Rician.

I. INTRODUCTION

The Pacific South East Asian region is expected to see an annual air traffic growth rate of 5.3% between 2012 to 2032 [1]. Such air traffic growth causes demand for data communications to intensify, causing a considerable amount of strain on current aeronautical communication systems. With existing aeronautical communication systems being inadequate at meeting the needed data capacity [2], communication technologies such as Aeronautical Mobile Airport Communications System (AeroMACS) and L-band Digital Aeronautical Communication System (LDACS) have been proposed to boost the capacities of Air-to-Ground (A/G) and Air-to-Air (A/A) links. However, the proposed solutions do not address the lack of aeronautical spectrum which the aviation industry is currently facing.

To this end, a hybrid-duplex (HBD) aeronautical communication system consisting of half-duplex (HD) and full-duplex (FD) nodes is a viable alternative to address the spectral crunch directly in aeronautical communications. FD systems enable nodes to simultaneously transmit and receive signals on the same frequency, effectively doubling the spectral efficiency [3], [4], [5]. Already, HBD systems have been investigated for cognitive radio systems [6] and cellular systems [7], [8], [9] to boost overall spectral efficiency.

Due to the simultaneous signal transmission and reception nature of FD systems, self-interference (SI) is unavoidable. To this end, a variety of passive and active SI mitigation architectures have been studied [10], [11], [12]. Passive SI mitigation architectures entail mitigating SI through path loss inducement (e.g. antenna separation) while active SI mitigation architectures suppress SI in the analog or digital domain. The latter can be further classified into pre-mixer, post-mixer or baseband, cancelers, where the cancellation signal is produced before down before or after the mixer, or at baseband respectively. Combining pre-mixer, post-mixer or baseband cancelers in a cascade is also a possibility.

Digital and analog SI cancellation have been associated with unique limitations [10]. Digital SI cancellation architectures are constrained by an ADC's dynamic range [4] while analog SI cancellation architectures require complex hardware. Apart from the associated limitations for both digital and analog SI cancellation, residual SI is also present in FD nodes due to phase noise and imperfect SI channel estimation [10]. Residual SI can affect the quality of communications hence restricting the amount of residual SI in aeronautical HBD systems is crucial for multiple aeronautical communication systems to co-exist on the same spectrum.

Therefore in this work, performance analysis of an HBD aeronautical communications system consisting of an FD ground station (GS) in an A/G link and two HD air-stations (ASs) operating current/legacy avionics systems is conducted. In particular, the HBD and HD system level outage probability and total transmission power requirements are analyzed for different distances between ASs under the effect of residual SI. The organization of this paper is as follows. The system model is introduced in Section II, with outage probability expressions presented in Section III. Numerical results are presented and discussed in Section IV before the conclusion of the paper in Section V.

II. SYSTEM MODEL

We assume two HD ASs communicating with an FD enabled GS node in an A/G link as shown in Fig. 1. Specifically, we assume a scenario with Air-Station 1 (AS-1) transmitting signals to the GS while Air-Station 2 (AS-2) is receiving signals from the GS. Since GS is an FD enabled node, the

Fig. 1. Air-Station 1 (AS-1) and Air-Station 2 (AS-2) operating in HD mode communicating with the FD ground station (GS).

HD AS-1 and HD AS-2 will respectively be transmitting and receiving signals in the same time slot on the same aeronautical spectrum (e.g. VHF) as the GS. Therefore, AS-2 will be experiencing interference from AS-1 when it receives signals from GS. An interference ignorant approach at AS-2 is adopted in this work, i.e., treating interference from AS-1 as noise, while assuming SI mitigation at GS. This approach enables performance analysis of a HBD aeronautical communication system, with minimal changes required for existing/legacy HD systems that are currently onboard aircrafts. It should also be noted that an en route scenario is assumed in this work, i.e., the ASs are communicating with the GS at cruising altitude, and the distances between the GS and ASs are assumed to be approximately equal ($d_{G,2} \approx d_{1,G}$). Thus, Rician fading is considered for both the SI channel (h_{si}) and the aeronautical communications channels ($h_{1,G}$, $h_{G,2}$, $h_{1,2}$) [13].

In this work, we propose an FD enabled GS with a combined pre-mixer and post-mixer SI cancellation architecture (Fig. 1). The SI signal is first mitigated using an analog domain pre-mixer canceler before it is down-converted and further mitigated via a digital domain post-mixer canceler. This combination of pre-mixer and post-mixer cancellation will result in less residual SI [10, Table II]. However, separate radio chains need to be implemented which can introduce unnecessary carrier phase noise. To reduce the effect of phase noise, the proposed SI cancellation architecture will share a common local oscillator (LO) (Fig. 1).

The signal model in this work is based on [10]. Let the signal-of-interest (SOI) and SI signal at GS be $x_1[t]$ and $x_{si}[t]$, respectively, and define the received signal at GS as

$$y_{GS}[t] = \sqrt{P_{r1,G}} h_{1,G}[t] x_1[t] + \sqrt{P_{r,si}} h_{si}[t] x_{si}[t] + w_G[t], \quad (1)$$

where $h_{1,G}[t]$ is the channel from AS-1 to GS and h_{si} is the SI channel coefficient. Also, let $w_G[t]$ be the GS additive white Gaussian noise (AWGN) with zero mean and variance σ_G^2 , and let the phase noise term $w_\phi[t]$ follow a Gaussian distribution with zero mean and unit variance, scaled by residual SI power γ_ϕ [10]. Additionally, let $P_{r1,G}$ be the received AS-1 power,

based on the free space path loss model, and define it as

$$P_{r,x,y} = \frac{P_{t,x}}{\left(\frac{4\pi \cdot 10^9}{3 \cdot 10^8}\right)^2 \cdot f_c^2 \cdot d_{x,y}^n \cdot \sigma_y^2}, \quad x \in \{1, G, si\}, y \in \{G, 2\}, \quad (2)$$

where $P_{t,x,y}$, d , f_c , n and σ^2 are the transmit power (Watts), distance (Km), carrier frequency (MHz), pathloss exponent, and noise power, respectively. Also, let the received SI power be $P_{r,si}$, and let $P_{r,si} = P_{t,G}$. The received signals are normalized with the noise variance and the receiver noise is assumed to have unit variance.

At AS-2, the SOI is $x_{GS}[t]$, and the interfering signal in this instance is from AS-2 i.e., $x_1[t]$. Let $P_{rG,2}$ and $P_{r,1,2}$ be the respective received powers of GS and AS-1 at AS-2. Thus, the received signal at AS-2 is

$$y_2[t] = \sqrt{P_{rG,2}} h_{G,2}[t] x_{GS}[t] + \sqrt{P_{r,1,2}} h_{1,2}[t] x_1[t] + w_2[t], \quad (3)$$

where $h_{G,2}[t]$ is the channel between GS and AS-2, $h_{1,2}[t]$ is the channel between AS-1 and AS-2, and $w_2[t]$ is the additive white Gaussian noise at AS-2 with variance σ_2^2 .

III. ANALYSIS OF OUTAGE PROBABILITIES

As the system reflected in Fig. 1 is a multi-user system, the overall system level outage probability will be used as a metric to compare HBD and HD system performance. We first define the respective HBD outage events at GS and AS-2 as

$$O_{GS}^{HBD} = \left\{ h_{1,G}, h_{si} : R_1^{HBD} \geq \log_2 \left(1 + SINR_{GS}^{HBD} \right) \right\} \quad (4)$$

$$O_2^{HBD} = \left\{ h_{G,2}, h_{1,2} : R_{GS}^{HBD} \geq \log_2 \left(1 + SINR_2^{HBD} \right) \right\} \quad (5)$$

where R_1^{HBD} and R_{GS}^{HBD} are the HBD transmission rates of AS-1 and GS, respectively, $SINR_{GS}^{HBD}$ and $SINR_2^{HBD}$ are the signal-to-interference-plus-noise ratios (SINRs) at GS and AS-2 respectively. Also, let the sum rate of the HBD system be $R_{sum}^{HBD} = R_{GS}^{HBD} + R_1^{HBD}$. The respective HD outage event at GS and AS-2 is similarly expressed as

$$O_{GS}^{HD} = \left\{ h_{1,G} : R_1^{HD} \geq \frac{1}{2} \log_2 \left(1 + SNR_{GS}^{HD} \right) \right\} \quad (6)$$

$$O_2^{HD} = \left\{ h_{G,2} : R_{GS}^{HD} \geq \frac{1}{2} \log_2 \left(1 + SNR_2^{HD} \right) \right\}, \quad (7)$$

where R_1^{HD} and R_{GS}^{HD} are the HD transmission rates of AS-1 and GS, respectively, SNR_{GS}^{HD} and SNR_2^{HD} are the signal-to-noise ratios (SNRs) at GS and AS-2, respectively. Similarly, the sum rate of the HD system is expressed as $R_{sum}^{HD} = R_{GS}^{HD} + R_1^{HD}$. The factor $\frac{1}{2}$ in (6) and (7) is due to the half-duplex mode. Then, the system level outage probability is defined as

$$P_{out,system}^\beta = \max (Pr(O_{GS}^\beta), Pr(O_2^\beta)), \beta \in \{HBD, HD\}. \quad (8)$$

1) *HBD Outage Probability*: When the GS is operating in FD mode, AS-1 will be transmitting signals to GS while AS-2 will be receiving signals from GS in the same time slot. This simultaneous transmission causes GS to receive very strong SI, and AS-2 to experience interference from AS-1. Thus, $SINR_{GS}^{HBD} = \frac{P_{r1,G}|h_{1,G}|^2}{P_{r,si}|h_{si}|^2\gamma_\phi^2 + \sigma_G^2}$ and $SINR_2^{HBD} = \frac{P_{rG,2}|h_{G,2}|^2}{P_{r,1,2}|h_{1,2}|^2 + \sigma_2^2}$. The HBD threshold is defined as $\gamma_{th,i}^{HBD} = 2^{R_i^{HBD}} - 1, i \in \{2, GS\}$ [14], [15], [16] and the outage probability at AS-2 is expressed as

$$\begin{aligned} Pr(O_2^{HBD}) &= Pr\{SINR_2 < \gamma_{th,2}^{HBD}\} \\ &= Pr\{X_{GS} < \gamma_{th,2}^{HBD}(Y_1 + \sigma_2^2)\}, \end{aligned} \quad (9)$$

where $X_{GS} = P_{rG,2}|h_{G,2}|^2$, $Y_1 = P_{r,1,2}|h_{1,2}|^2$. In particular, X_{GS} and Y_1 are both independent non-centered Chi-squared distributed random variables (RVs) with identical Rician K factors (K_{Rice}). The outage probability in (9) is then approximated [17] as

$$Pr(O_2^{HBD}) \approx \sum_{k=1}^{K_{tr}} a_k (\gamma_{th,2}^{HBD})^{b_k} \sum_{i=0}^{b_k} \binom{b_k}{i} (\sigma_2^2)^{b_k-i} E\{Y_1^i\}, \quad (10)$$

where $a_k = \frac{(-1)^k \exp(-K_{Rice}) L_k^{(0)}(K_{Rice}) (1+K_{Rice})^{k+1}}{(1+k)!(P_{rG,2})^{k+1}}$, $E\{Y_1^i\} = \frac{\Gamma(1+i)}{(1+K_{Rice})^i} {}_1F_1(-i, 1; -K_{Rice})(P_{r,1,2})^i$, $b_k = k + 1$ and K_{tr} is the order of truncation. The functions $L_k^{(0)}(\bullet)$ and ${}_1F_1(\bullet)$ represents the i -th degree, zero-order Laguerre polynomials and the confluent Hypergeometric function, respectively.

Likewise, the outage probability at GS can be expressed as

$$Pr(O_{GS}^{HBD}) = Pr\{X_1 < \gamma_{th,GS}^{HBD}(Y_{si} + \sigma_G^2)\}, \quad (11)$$

where $X_1 = P_{r1,G}|h_{1,G}|^2$ and $Y_{si} = P_{r,si}|h_{si}|^2\gamma_\phi^2$. In particular, X_1 and Y_{si} are both independent non-centered Chi-squared distributed RVs with identical K_{Rice} . The outage probability in (11) is approximated as

$$Pr(O_{GS}^{HBD}) \approx \sum_{k=1}^{K_{tr}} \lambda_k (\gamma_{th,GS}^{HBD})^{b_k} \sum_{i=0}^{b_k} \binom{b_k}{i} (\sigma_G^2)^{b_k-i} E\{Y_{si}^i\}. \quad (12)$$

In (12), λ_k and $E\{Y_{si}^i\}$ are based on X_1 and Y_{si} , respectively, and are computed in a similar manner to a_k and $E\{Y_1^i\}$ in (10). In order for (10) and (12) to converge, both $\gamma_{th,2}^{HBD}$ and $\gamma_{th,GS}^{HBD}$ are upper bounded by $\frac{P_{rG,2}}{2P_{r1,2}}$ and $\frac{P_{r1,G}}{2P_{r,si}}$, respectively.

2) *HD Outage Probability*: When the GS is operating in HD mode, AS-2 will not experience interference from AS-1. Thus $SINR_{GS}^{HD} = \frac{P_{r1,G}|h_{1,G}|^2}{\sigma_G^2}$ and $SINR_2^{HD} = \frac{P_{rG,2}|h_{G,2}|^2}{\sigma_2^2}$. The HD threshold is defined as $\gamma_{th,i}^{HD} = 2^{2R_i^{HD}} - 1, i \in \{2, GS\}$. Assuming that both ASs are in the en route scenario, i.e., $h_{1,G}$ and $h_{G,2}$ are Rician faded, the outage probabilities at AS-1 and GS are $Pr(O_{GS}^{HD}) = 1 - Q_1\left(\sqrt{2K_{Rice}}, \sqrt{\frac{2(K_{Rice}+1)\gamma_{th,GS}^{HD}\sigma_G^2}{P_{r1,G}}}\right)$ and $Pr(O_2^{HD}) = 1 - Q_1\left(\sqrt{2K_{Rice}}, \sqrt{\frac{2(K_{Rice}+1)\gamma_{th,2}^{HD}\sigma_2^2}{P_{rG,2}}}\right)$, respectively, where $Q_1(\cdot, \cdot)$ is the Marcum Q function [17].

IV. NUMERICAL RESULTS

Fig. 2. System level outage probability versus received power of SOI (Ω). $K_{tr} = 80$, $\sigma_G^2 = \sigma_2^2 = -115dBm$, $K_{Rice} = 15$, $R_{sum}^{HD} = R_{sum}^{HBD} = 1$ b/s/Hz.

The system level performance of the A/G link consisting of two HD ASs and the FD GS (Fig. 1) is discussed here. To investigate the impact of inter AS separation on the HBD system level outage probability ($P_{out,system}^{HBD}$), the distances between the GS and ASs are assumed to be equal, i.e., $d_{G,2} = d_{1,G}$. With this assumption, we let the received SOI powers at AS-2 and GS be equal, i.e., $P_{r1,G} = P_{rG,2} = \Omega$ and evaluate $P_{out,system}^{HBD}$ under various inter AS separations by assuming $d_{1,2} = \alpha d_{G,2}$. We further assume $f_c = 136.725$ MHz (VHF) and $n = 6$ in this work [18], [19]. From (2), it can be easily shown that

$$P_{r1,2} = \frac{P_{t,1}}{\left(\frac{4\pi \cdot 10^9}{3 \cdot 10^8}\right)^2 \cdot f_c^2 \cdot (\alpha d_{G,2})^n \cdot \sigma_2^2} \quad (13)$$

The HBD system level outage probabilities ($P_{out,system}^{HBD}$) is evaluated by varying α and residual SI power (γ_ϕ^2), and compared against $P_{out,system}^{HD}$. To maintain a fair comparison, we also assume the transmission rates for both HBD and HD modes to be the same.

Fig. 2 shows the system level outage probability and it can be seen that the HBD system outperforms the HD system when Ω is small and $\alpha = 1$. In fact, $P_{out,system}^{HBD}$ is lower than $P_{out,system}^{HD}$ when $\Omega \leq 1.5dB$, $\alpha = 1$ and $\gamma_\phi^2 = \sigma_G^2 = -115dBm$. Under such conditions, $d_{1,2} = d_{G,2}$ thus leading to the interfering signal from AS-1 and SOI having the same received power at AS-2. From (4) to (7), it can be easily shown that a HBD system can support the same data rate as a HD system with lesser SINR, thus explaining the trend seen in Fig. 2. In addition, the performance bottleneck when $\alpha = 1$ and $\gamma_\phi^2 = -115dBm$ is at AS-2. This is because the interfering AS-1 signal at AS-2 is strong, causing $Pr(O_2^{HBD}) > Pr(O_{GS}^{HBD})$.

As α is increased, $P_{out,system}^{HBD} < P_{out,system}^{HD}$ even when γ_ϕ^2 is increased and $\Omega < 12dB$. For $\gamma_\phi^2 = -115dBm$ and $\alpha = \{1.5, 2\}$, the results from Fig. 2 shows that varying α does not affect the outage probabilities when $\Omega \leq 10.5dB$. As α is

TABLE I
SUMMARY OF HBD PERFORMANCE BOTTLENECK

α	γ_ϕ^2	GS (dB)	AS-2 (dB)	$P_{out,system}^{HBD} \leq 10^{-3}$
1	-115 dBm	-	$\Omega \geq 0$	-
1.5	-130 dBm	-	$\Omega \geq 0$	$\Omega \geq 4$ dB
2	-130 dBm	$0 \leq \Omega \leq 3$	$\Omega > 3$	$\Omega \geq 3.5$ dB
1.5	-115 dBm	$0 \leq \Omega \leq 10$	$\Omega > 10$	$\Omega \geq 6.5$ dB
2	-115 dBm	$\Omega \geq 0$	-	$\Omega \geq 6.5$ dB

increased to $\alpha = \{1.5, 2\}$, the interfering AS-1 signal at AS-2 is weakened, thus leading to $Pr(O_2^{HBD}) < Pr(O_{GS}^{HBD})$. As a result, system level outage is dominated by GS. In fact, when $\alpha = 2$ and $\gamma_\phi^2 = -115$ dBm, the performance bottleneck is at GS for all values of Ω in Fig. 2. However, when $\alpha = 1.5$, $\gamma_\phi^2 = -115$ dBm and $\Omega \geq 11$ dB, the performance bottleneck is at AS-2. As Ω increases, interference from AS-1 becomes stronger, causing $Pr(O_2^{HBD}) > Pr(O_{GS}^{HBD})$. When γ_ϕ^2 is reduced to -130 dBm and $\alpha = 1.5$, $Pr(O_2^{HBD}) > Pr(O_{GS}^{HBD})$ despite a weaker interfering AS-1 signal at AS-2. As a consequence, $P_{out,system}^{HBD}$ is dominated by AS-2 for all values of Ω in Fig. 2. Letting $\gamma_\phi^2 = -130$ dBm and $\alpha = 2$ causes the interfering AS-1 signal at AS-2 to further weaken. When $\Omega \leq 3$ dB, $Pr(O_2^{HBD}) < Pr(O_{GS}^{HBD})$, thus the performance bottleneck is at GS. As Ω increases beyond 3 dB, $Pr(O_2^{HBD}) > Pr(O_{GS}^{HBD})$, thus the performance bottleneck shifts to AS-2.

A summary of the performance bottleneck of the HBD system can be seen in Table I. The third and fourth column indicates the range of Ω for which the performance bottleneck is at GS and AS-2 respectively, as α and γ_ϕ^2 is varied. The fifth column indicates the required Ω to attain $P_{out,system}^{HBD} \leq 10^{-3}$. The results seen in Fig. 2 indicates that a HBD aeronautical communications system can outperform a HD aeronautical communications system even when AS-2 is made an interference ignorant receiver, i.e., treats interference as noise. The results in Fig. 2 also shows that varying the distance between ASs can drastically improve the communications reliability, e.g., when $\alpha = 1$ and $\alpha = 1.5$. The effect of residual SI was also demonstrated in Fig. 2 when γ_ϕ^2 was varied. In particular, $P_{out,system}^{HBD}$ improved when γ_ϕ^2 was reduced and vice versa. It has been shown by Sahai et al. [10] that residual SI is caused by imperfect analog and digital SI channel estimation. Therefore, an ideal HBD aeronautical communications system will be one where residual SI power is kept to a minimum via either appropriate channel estimation techniques or residual SI mitigation.

Fig. 3 shows the total transmit power to maintain communication at $P_{out,system}^\beta \leq 10^{-3}$ where $\beta \in \{HBD, HD\}$. We let the transmit powers $P_{t,G} = P_{t,1}$, and contrast the total transmit power requirements ($P_{t,G} + P_{t,1}$) in order to maintain a certain level of reliability in an A/G communications link. We only consider $\alpha = \{1.5, 2\}$, $\gamma_\phi^2 = \{-130$ dBm, -115 dBm} in Fig. 3 since $\alpha = 1$ causes $P_{out,system}^{HBD}$ to have an error floor as Ω increases. For a HD system to maintain communication at $P_{out,system}^{HD} \leq 10^{-3}$, the minimum received power required is $\Omega = 7$ dB as seen in Fig. 2. In the case of a HBD system, the

Fig. 3. Comparison between total transmit power needed and distance from GS to both ASs for outage probability $\leq 10^{-3}$.

value of Ω to ensure that $P_{out,system}^{HBD} \leq 10^{-3}$ for $\alpha = \{1.5, 2\}$, $\gamma_\phi^2 = \{-130$ dBm, -115 dBm} can similarly be found in Fig. 2, and it is also summarized in Table I.

It is evident from Fig. 3 and Table I that a higher level of total transmit power is required for the HD system to maintain $P_{out,system}^{HD} \leq 10^{-3}$ as compared to a HBD system. Since (4) to (7) shows that the HBD system can support the same data rate as a HD system with a lower SINR, it also implies that the HBD system has lower transmit power requirements than the HD system. In terms of transmission range, this translates to superior communications range compared to the HD system under the same total transmit power requirements (Fig. 3) and is demonstrated in Fig. 3 for $\alpha = 2$, $\gamma_\phi^2 = -130$ dBm where the total transmit power required for HD and HBD systems is a difference of 3.5 dBm. This reduction in the transmit power leads to an increase in additional transmission range of between 1.5 Km to 4 Km. When $\alpha = 1.5$ and $\gamma_\phi^2 = -130$ dBm, the total transmit power difference between HD and HBD systems reduces to 3 dBm due to the reduced distance between ASs, i.e., smaller $d_{1,2}$, causing the interfering AS-1 signal at AS-2 to be stronger. As a consequence, the total transmit power requirement increases to maintain $P_{out,system}^{HBD} \leq 10^{-3}$. However, an additional transmission range of between 1 Km to 3 Km is still possible when compared to a HD system.

When residual SI power is increased, i.e., $\gamma_\phi^2 = \sigma_G^2 = -115$ dBm, communications at the FD GS is noisy since the denominator component of $SINR_{GS}^{HBD}$ is effectively doubled and is true for $\alpha = 1.5$ and $\alpha = 2$ thus necessitating an even higher amount of transmit power at AS-1. Consequently, a higher total transmit power is required than when $\alpha = \{1.5, 2\}$ and $\gamma_\phi^2 = -130$ dBm. The resultant total transmit power difference between HBD and HD systems is thus only 0.5 dBm (Fig. 3), resulting in maximum additional transmission range of less than 1 Km when compared to HD systems. From Fig. 3, it is evident that the HBD aeronautical communications system enjoys lower transmission power requirements and increased transmission range on top of improved reliability in A/G communications compared to that of the HD based

system. However, this is only possible if residual SI power is below the receiver noise floor.

Fig. 4. Comparison between system level outage probability and distance from GS to both ASs.

In Fig. 4, we let $d = d_{1,G} = d_{G,2}$, $\alpha = \{1, 1.5, 2\}$, $\gamma_\phi^2 = -130\text{dBm}$, $P_{t,1} = P_{t,G} = 43\text{dBm}$, $\sigma_G^2 = \sigma_{noise,1}^2 = -115\text{dBm}$. The distance $d = d_{1,G} = d_{G,2}$ represents the distance from GS to both ASs, and it is varied to demonstrate the effect of d on $P_{out,system}^\beta$, $\beta \in \{HBD, HD\}$. From Fig. 4, $P_{out,system}^{HBD} < P_{out,system}^{HBD}$ when $\alpha = 1$. This is because $d_{1,2} = d$ leading to AS-2 experiencing strong interference from AS-1 when operating in HBD mode as compared to HD mode where no interference is present at AS-2. Therefore $SINR_2^{HBD} < SINR_2^{HD}$ when $\alpha = 1$. Fig. 4 also shows the additional transmission range that a HBD system will enjoy. When $\alpha = \{1.5, 2\}$, $P_{out,system}^{HBD} < P_{out,system}^{HD}$. Increasing α leads to greater separation distance between the ASs, thus resulting in weaker interference at AS-2. Together with low SINR requirements of a HBD system, both ASs can fly closer to GS while maintaining HBD A/G communications that are even more reliable than a HD A/G link.

V. CONCLUSION

The scarcity of available aeronautical communications spectrum and insufficient capacities of current A/G links to meet rising data demands are issues that must be tackled in due time. To improve aeronautical spectral efficiency and achievable data rate, we propose a HBD aeronautical communications system consisting of an FD enabled GS and interference ignorant HD ASs. System level outage probability and total transmission power requirements are then compared for both HBD and HD mode of operations. Our analysis have shown that the proposed HBD aeronautical communications system supports A/G communications that are more reliable than HD systems in an en route scenario. The proposed system is also able to operate with less transmission power and longer transmission range when supporting the equivalent HD system data rate. As this work only evaluated system performance for Rician faded aeronautical channels, work is in progress on

conducting similar analysis for a mix of Rician and Rayleigh faded channels where the ASs are en route, arriving, landing or parking at an airport. Further analysis for a mix of the mentioned scenarios for varying values of K_{rice} , $d_{1,G}$, $d_{G,2}$ and $d_{1,2}$ is also being investigated.

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