A hybrid-duplex system with joint detection for interference-limited UAV communications

Tan, Ernest Zheng Hui; Madhukumar A. S.; Sirigina, Rajendra Prasad; Krishna, Anoop Kumar

2018

Tan, E. Z. H., Madhukumar, A. S., Sirigina, R. P., & Krishna, A. K. (2018). A hybrid-duplex system with joint detection for interference-limited UAV communications. IEEE Transactions on Vehicular Technology, 68(1), 335-348. doi:10.1109/TVT.2018.2878889

<https://hdl.handle.net/10356/136853>

<https://doi.org/10.1109/TVT.2018.2878889>

© 2018 IEEE. Personal use of this material is permitted. Permission from IEEE must be obtained for all other uses, in any current or future media, including reprinting/republishing this material for advertising or promotional purposes, creating new collective works, for resale or redistribution to servers or lists, or reuse of any copyrighted component of this work in other works. The published version is available at:
<https://doi.org/10.1109/TVT.2018.2878889>

Downloaded on 26 Apr 2023 11:41:17 SGT

A Hybrid-Duplex System with Joint Detection for Interference-Limited UAV Communications

Tan Zheng Hui Ernest, A S Madhukumar, Rajendra Prasad Sirigina, and Anoop Kumar Krishna

Abstract—In this work, the advantages of joint detection (JD) in a hybrid-duplex unmanned aerial vehicle (UAV) communication system (HBD-UCS) are investigated as a step towards addressing spectrum scarcity in UAV communications. Through extensive outage probability and finite signal-to-noise-ratio (SNR) diversity gain analysis, we showed that the performance of joint detection (JD) is independent of the strength and the data rate of the inter-UAV interference signal. On the contrary, the successive interference cancellation (SIC) detector requires the data rate of the interfering UAV to be less than the ground station before meaningful performance can be seen. At the system level, it is observed that the half-duplex UAV communication system outperforms the HBD-UCS with JD at moderate and high SNR regimes, as the latter is constrained by self-interference at the full-duplex ground station. Lastly, we investigated the multiplexing gain region and showed that the joint detector offers higher diversity gain over a wide range of multiplexing gains over the interference ignorant (II) and the SIC detector.

Index Terms—Unmanned Aerial Vehicle, Multiplexing Gain Region, Spectral Utilization, Full-Duplex, Hybrid-Duplex, Half-Duplex, Outage Probability, Rician, Finite signal-to-noise ratio (SNR), Diversity.

I. INTRODUCTION

IN recent years, unmanned aerial vehicles (UAVs) have been increasingly used for various purposes, including the surveying of terrain [1], telecommunications relaying [2], and vehicular communications [3], [4]. In particular, the deployment of multi-UAV networks, i.e., swarms of UAVs, has seen interest from both industry and academia as a means towards addressing the limited payload and flight time of individual UAVs [1] and the lack of link redundancy in single-UAV networks [5]. Already, the deployment of multiple UAVs in the same network as flying base stations has been studied as a means to provide cellular service for ground users [6].

A. Motivation and Related Literature

Despite the potential benefits of multi-UAV networks, many challenges remain. One notable instance is the allocation of

L-band and C-band spectrum by the International Telecommunications Union (ITU) for UAV communications, e.g., for control and non-payload communication (CNPC) applications [7]. However, there is limited available spectrum for UAV communications as many other systems, e.g., aeronautical communication systems, also operate on L-band and C-band [7]. Therefore, spectrum scarcity in UAV communications is an issue that must be addressed in due time.

To this end, a hybrid-duplex (HBD) UAV communication system (UCS), i.e., HBD-UCS, consisting of UAVs with legacy half-duplex (HD) communication systems and full-duplex (FD) ground stations (GSs), has been studied as a viable alternative to improve spectrum utilization with minimal disruptions [8]. In HBD systems, both HD and FD-enabled nodes operate concurrently on the same spectrum, leading to improved spectrum utilization. However, HBD systems are impaired by self-interference (SI) due to the simultaneous transmission and reception of signals, which can be passively suppressed (through inducing path loss) or canceled in the analog or digital domain. Also, residual SI, due to inherent carrier phase noise and imperfect SI channel estimation can potentially degrade the performance of FD transceivers [9]. As such, implementing suitable SI mitigation architectures are a necessity in HBD systems. Additionally, we note that opting for an FD-UCS, i.e., UAVs and GSs operating in FD mode, results in better spectrum utilization over the HBD paradigm. However, constraints imposed on the size, weight, and power requirements of UAVs may cause FD transceiver designs to be infeasible. Therefore, opting for an HBD-UCS allows spectrum utilization to be addressed while retaining existing HD-UCS, with related applications seen in aeronautical communication systems [10], [11].

Apart from SI, inter-UAV interference is also present at the HD UAVs in the HBD-UCS. In this aspect, interference management strategies, such as the interference ignorant (II), successive interference cancellation (SIC), or the joint detection (JD) strategies, can be adopted to mitigate inter-UAV interference. The II approach regards interference as noise and is optimal in weak interference scenarios [12], [13] while the SIC approach, which first removes interference before detecting the signal-of-interest (SOI), is effective in strong interference scenarios [14], [15]. On the other hand, the JD approach jointly decodes the SOI and interference at the receiver, and is optimal when strong interference is present albeit at the cost of high computational complexity [16], [17]. In [10] and [11], outage probability analysis of HBD aeronautical communication systems showed that the II and the SIC strategies are interference-limited at high SNR regimes

Copyright (c) 2015 IEEE. Personal use of this material is permitted. However, permission to use this material for any other purposes must be obtained from the IEEE by sending a request to pubs-permissions@ieee.org.

Tan Zheng Hui Ernest is with the School of Computer Science and Engineering, Nanyang Technological University, Singapore e-mail: (tanz0119@e.ntu.edu.sg).

A S Madhukumar is with the School of Computer Science and Engineering, Nanyang Technological University, Singapore e-mail: (asmadhukumar@ntu.edu.sg).

Rajendra Prasad Sirigina is with the School of Computer Science and Engineering, Nanyang Technological University, Singapore e-mail: (raje0015@ntu.edu.sg).

Anoop Kumar Krishna is with Airbus Singapore Pte Ltd, Singapore e-mail: (anoopkumar.krishna@airbus.com).

and are effective in weak and strong interference scenarios, respectively. However, in the context of UAV communications, suitable interference management strategies to handle the various levels of inter-UAV interference in multi-UAV systems have still yet not been identified.

Another issue in HBD-UCS is the need to concurrently meet Quality-of-Service (QoS) requirements for both CNPC links and non-CNPC links as a result of simultaneous communications over a common spectrum¹. To safely operate multi-UAV systems, CNPC links have high reliability and low data rate requirements [19]. On the other hand, non-CNPC links, i.e., data links, have higher data rate requirements than CNPC links, which is dependent on the task at hand [19]. As the QoS requirements of both CNPC and non-CNPC links must be concurrently satisfied in the HBD-UCS, the extent of reliability tradeoffs for higher transmission rates in the presence of inter-UAV interference is still not yet known. More importantly, it still remains to be seen if the HBD-UCS can better meet the necessary QoS requirements compared to existing HD-UCS.

To this end, the finite signal-to-noise ratio (SNR) diversity gain and finite SNR diversity-multiplexing trade-off (DMT) of the HBD-UCS can be analyzed. The finite SNR diversity gain and finite SNR DMT describes outage probability decay rate (reliability) at a particular SNR [20], with multiplexing gain (data rate) considered in the latter [21]. Such analysis reveals the outage probability behavior of the HBD-UCS at low SNR regimes, which is lost at asymptotic SNRs [20]. A corresponding multiplexing gain region (MGR) of the HBD-UCS can also be determined [22] to identify the multiplexing gains of the interfering and desired transmitters that achieves non-zero diversity gains. Through diversity gain and MGR analysis, the supported QoS range of the HBD-UCS, along with the necessary conditions to achieve non-zero diversity gains, e.g., inter-UAV interference levels and data rates, for various interference management strategies can be identified.

In this article, we investigate the potential advantages of JD in an HBD-UCS in terms of reliability and supported QoS ranges. To this end, the main contributions of this paper are summarized below.

B. Main Contributions

- A novel approach to obtain closed-form expressions for the outage probability and finite SNR diversity gain (for both fixed and variable transmission rates) of a joint detector over Rician fading channels is presented in this paper.
- We demonstrate that the outage probability and diversity gain of the joint detector is independent of the inter-UAV interference levels in moderate and high SNR regimes.
- At moderate and high SNR regimes, we observe that the system level performance of the HBD-UCS with JD is suboptimal due to SI at the GS.
- We show that the diversity gain of the joint detector is independent of the data rate of the interfering signal when

¹To enable the sharing of the spectrum for CNPC and non-CNPC links with joint detector, the block length of the codes used, e.g., LDPC codes, should be the same [18].

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).

inter-UAV interference is sufficiently strong. In contrast, the SIC detector requires the data rate of the interfering signal from the HD UAV to be lower than the data rate of the SOI from the FD-enabled GS to achieve non-zero diversity gain.

- Through MGR analysis, we show that the JD-based HBD-UCS achieves superior finite SNR diversity gain, i.e., reliability, while supporting a wider range of QoS requirements than the II-based and the SIC-based HBD-UCS.

The remainder of this paper is organized as follows. The proposed system model is introduced in Section II, with outage probability and finite SNR diversity gain derivations for the joint detector presented in Section III and Section IV, respectively. The results of the numerical analysis are presented in Section V before the conclusion of the paper in Section VI.

II. SYSTEM MODEL

Fig. 1 shows the proposed HBD-UCS for UAV communications in a suburban environment between an FD-enabled GS node and two HD unmanned aerial vehicles (UAVs). In particular, Unmanned Aerial Vehicle 1 (UAV-1) transmits non-CNPC data to the GS while Unmanned Aerial Vehicle 2 (UAV-2) concurrently receives CNPC data from the GS on the same spectrum, e.g., L-band. Two antennas, one for transmission and another for reception of signals, with a shared local oscillator are assumed at the FD-enabled GS. Also, the Doppler effect as a result of UAV mobility is assumed to be compensated. Clearly, spectrum utilization is improved at the expense of introducing self-interference (SI) and inter-UAV interference at the FD-enabled GS and UAV-2, respectively. To enable realistic modeling of the suburban environment, Rician fading is assumed on all UAV communication channels [7]. Additionally, the SI signal is assumed to undergo passive SI mitigation before active SI mitigation at the FD-enabled GS. Thus, we consider only residual SI at the FD-enabled GS, with the SI link (h_{si}) modeled as a Rician fading channel to account for passive and active SI mitigation [23].

A. Ground Station

At the FD-enabled GS, let $x_{gs}[t]$ and $x_1[t]$ be the transmitted signals from GS and UAV-1, respectively, where the signal-of-interest (SOI) and the SI signal are $x_1[t]$ and $x_{si}[t] = x_{gs}[t]$, respectively. Additionally, let $h_{1,g}[t]$ be the channel between

UAV-1 and GS, and h_{si} be the SI channel gain. Then, the received signal at GS can be written as [9]:

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

where $\tilde{h}_{si}$ is the error of the imperfect SI channel gain estimate, defined as $\tilde{h}_{si} = h_{si} - \hat{h}_{si}$, and $\hat{h}_{si}$ is the imperfect estimation of the SI channel gain. To model the worst case residual SI, the channel estimation error ($\tilde{h}_{si}$) is modeled as a circularly symmetric zero-mean complex Gaussian random variable (RV) with variance ϵ [24].

Additionally, let the additive white Gaussian noise (AWGN) at GS be $w_g[t]$, 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 the strength of the phase noise γ_ϕ [9].

Let the average received signal power of the SOI, normalized with the GS receiver noise variance (σ_g^2), be Ω_X , which is related to the transmit power P_t (Watts) and distance $d_{1,g}$ (Km) as:

$$\Omega_X \propto \frac{P_t}{(d_{1,g})^n \sigma_g^2}, \quad (2)$$

where n is the pathloss exponent. We select the channel between UAV-1 and GS as the reference link, with the average received signal power in the other links expressed relative to the reference link to represent the inter-UAV interference level $\alpha_{i,j}$ as follows:

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

From (2) and (3), the average received SI power at GS can be expressed as $\Omega_X \alpha_{g,g}$.

B. Unmanned Aerial Vehicle 2

The SOI and the interfering signal at UAV-2 are $x_{gs}[t]$ and $x_1[t]$, respectively. Let $h_{g,2}[t]$ be the channel between GS and UAV-2, and let $h_{1,2}[t]$ be the channel between UAV-1 and UAV-2. Let $w_2[t]$ be the AWGN at UAV-2 with zero-mean and variance σ_2^2 . 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.

As interference is present at UAV-2, we consider three approaches to handle the interference. The first approach is to assume an II detector at UAV-2 by treating $x_1[t]$ as noise, thus effectively ignoring interference. The second approach assumes a two-stage SIC detector at UAV-2 where $x_1[t]$ is detected and removed before $x_{gs}[t]$ is detected [25]. The final approach assumes a joint detector where both $x_{gs}[t]$ and $x_1[t]$ are jointly detected [26].

²The scaling factor γ_ϕ models the jitter present in oscillators due to hardware imperfections [9]

Fig. 2. The achievable instantaneous rate regions of the II, SIC and joint detectors (unshaded areas) at UAV-2 with respect to the transmission rates of the GS (R_{GS}^{HBD}) and UAV-1 (R_1^{HBD}). The shaded areas, O_{JD}^1 and O_{JD}^2 , respectively denote the outage region of the joint detector if SOI detection fails or if the sum rate constraint is not met.

III. OUTAGE PROBABILITY DERIVATIONS

In this section, we derive the closed-form outage probability expression for the joint detector at UAV-2. As inter-UAV interference increases, we show that the outage probability of the joint detector approaches that of an interference-free UAV-2. We also define the system level outage probability, along with references for benchmark schemes, to identify bottlenecks in the proposed HBD-UCS system.

A. Joint Detector at UAV-2

Let R_1^i and R_{gs}^i be the transmission rates of UAV-1 and GS, respectively, where $i \in \{HBD, HD\}$, and $R_{sum}^i = R_1^i + R_{gs}^i$ be the sum rate of the system. To maintain the same sum rate, the transmission rate of HD systems must be twice that of HBD systems as spectrum is shared between nodes in the former [23], [27]. Thus, let $R_j^{HBD} = \frac{1}{2} R_j^{HD}$ for $j \in \{1, gs\}$ to maintain a fair comparison between HBD-UCS and HD-UCS.

At UAV-2, let the instantaneous received signal power of the SOI and the inter-UAV 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, where X_{gs} and Y_1 are independent non-centered Chi-squared distributed RV with respective Rician K factors $K_{X_{gs}}$ and K_{Y_1} .

To mitigate inter-UAV interference, the joint detector at UAV-2 simultaneously detects both SOI and interference from GS and UAV-1, respectively. The resultant instantaneous achievable rate region of the joint detector (A1 to A4), along with the II detector (A1 and A3) and the SIC detector (A1 and A2), are illustrated in Fig. 2. Based on the instantaneous achievable rate region, the HBD outage event of the joint detector at UAV-2 is defined as:

$$O_2^{HBD(JD)} = O_{JD}^1 \cup O_{JD}^2 \quad (5)$$

$$\text{where } O_{JD}^1 = \left\{ h_{g,2}, h_{1,2} : R_{gs}^{HBD} > \log_2 \left(1 + X_{gs} \right) \right\}, \quad (6)$$

$$O_{JD}^2 = \left\{ h_{g,2}, h_{1,2} : R_1^{HBD} + R_{gs}^{HBD} > \log_2 \left(1 + X_{gs} + Y_1 \right), \right. \\ \left. \log_2 \left(1 + \frac{X_{gs}}{1 + Y_1} \right) \leq R_{gs}^{HBD} \leq \log_2 \left(1 + X_{gs} \right) \right\}. \quad (7)$$

Remark 1: The joint detector outage event ($O_2^{HBD(JD)}$) occurs if SOI detection fails (O_{JD}^1) or if the sum rate constraint is not met (O_{JD}^2). Evidently, meeting the sum rate constraint (O_{JD}^2) enables the joint detector to attain a larger rate region than the II and the SIC detectors at the cost of complex hardware [17], [26].

In a two-user multiple access channel, the joint detector simultaneously decodes the two user's data streams as the SOIs. An outage event occurs if either of the streams cannot be decoded [25]. In contrast, only the signal from the FD-enabled GS is treated as the SOI while the signal from UAV-2 is treated as interference in the present work. Therefore, the joint detector tries to decode only the SOI, while utilizing the structure of the interfering signal. Consequently, the interfering signal can be transmitted at a higher rate than the capacity of the interfering link [28].

The advantages of the joint detector in the present work is evident in Fig. 2. In particular, (6) and (7) are obtained using the above principles. A similar decoding algorithm for an interference-limited receiver in a two-user interference channel is also investigated in [29], [30], where similar achievable instantaneous rate regions were obtained. For the II and SIC detectors, the respective achievable instantaneous rate regions are obtained using the outage events definition in [11]. Together, the achievable instantaneous rate regions in Fig. 2 form the basis for Remark 1.

Next, let $\bar{\alpha}(q, \Omega, K, \gamma)$ be the cumulative distribution function (CDF) expansion of a Rician fading channel, which is defined as:

$$\bar{\alpha}(q, \Omega, K, \gamma) = (-1)^q \exp(-K) \frac{L_q^{(0)}(K)}{(1+q)!} \left(\frac{(1+K)}{\Omega} \gamma \right)^{q+1}, \quad (8)$$

where q , Ω , K and γ represents an arbitrary non-negative integer, average received power of a Rician signal, Rician K factor and threshold, respectively, and $L_q^{(0)}(\bullet)$ represents the q -th degree, zero-order Laguerre polynomials [31]. Then, the closed-form outage probability expression for the joint detector is presented in the following theorem.

Theorem 1: The closed-form expression for the outage probability with joint detector at UAV-2 is:

$$\begin{aligned} Pr(O_2^{HBD(JD)}) &\approx 1 - Q_1 \left(\sqrt{2K_{X_{gs}}}, \sqrt{\frac{2(K_{X_{gs}} + 1)\gamma_{th,2}^{HBD}}{\Omega_X \alpha_{g,2}}} \right) \\ &+ \sum_{n=0}^{K_{tr}} \sum_{i=0}^n \sum_{j=0}^{i+1} \bar{\alpha}(i, \Omega_X \alpha_{1,2}, K_{Y_1}, 1) \bar{\alpha}(n-i, \Omega_X \alpha_{g,2}, K_{X_{gs}}, 1) \binom{i+1}{j} \\ &\times (-1)^{i+1} G_1(i, j, b_2, \gamma_{th,2}^{HBD}) \frac{G_2(j+n-i+1, b_1, \gamma_{th,2}^{HBD})}{j+n-i+1}, \quad (9) \end{aligned}$$

where K_{tr} is the truncation order, $\gamma_{th,2}^{HBD} = 2^{R_{gs}^{HBD}} - 1$ is the threshold, $b_1 = 2^{R_1^{HBD}}(2^{R_{gs}^{HBD}} - 1)$, $b_2 = 2^{R_1^{HBD} + R_{gs}^{HBD}} - 1$, $G_1(i, j, b_2, \gamma_{th,2}^{HBD}) = (-b_2)^{i+1-j} - (-\gamma_{th,2}^{HBD})^{-j}$, $G_2(j+n-i+1, b_1, \gamma_{th,2}^{HBD}) = (b_1)^{j+n-i+1} - (\gamma_{th,2}^{HBD})^{j+n-i+1}$ and $Q_1(\cdot, \cdot)$ is the Marcum Q function [31]

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

Remark 2: The first two terms on the right-hand side (RHS) of (9) are due to the outage event O_{JD}^1 . These two terms also

TABLE I
REFERENCES FOR THE OUTAGE PROBABILITY OF THE BENCHMARK SCHEMES

Protocol/Detector	Notation	Reference
II Detector at GS	$Pr(O_{gs}^{HBD})$	[11, eq. (6)]
II Detector at UAV-2	$Pr(O_2^{HBD(II)})$	[11, eq. (8)]
SIC Detector at UAV-2	$Pr(O_2^{HBD(SIC)})$	[11, eq. (10)]
HD-UCS at GS	$Pr(O_{gs}^{HD})$	[11, eq. (12)]
HD-UCS at UAV-2	$Pr(O_2^{HD})$	[11, eq. (13)]

correspond to the outage probability of an interference-free UAV-2. The third term on the RHS of (9) is due to the outage event O_{JD}^2 , where the functions $\bar{\alpha}(i, \Omega_X \alpha_{1,2}, K_{Y_1}, 1)$ and $\bar{\alpha}(n-i, \Omega_X \alpha_{g,2}, K_{X_{gs}}, 1)$ are due to the inter-UAV interference and SOI, respectively. From (9), it is evident that failure to either detect the SOI or meet the sum rate constraint contributes to outage probability.

The expression in (9) is only valid if the power series in the second term on the RHS converges, which is proven in the following theorem.

Theorem 2: The power series in (9) has a convergence radius of ∞ .

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

It should be noted that the differentiation of a convergent power series, e.g., (36), is also valid within the convergence radius [32], [33], which is useful for deriving expressions related to finite SNR analysis in the next section.

It is known that the joint detector is effective when strong interference is encountered [13], [16], [17], [26]. To investigate the effect of strong inter-UAV interference, we evaluate the limit of $\bar{\alpha}(i, \Omega_X \alpha_{1,2}, K_{Y_1}, 1)$ with respect to $\alpha_{1,2}$. In particular, we evaluate the limit for the extreme case of very strong inter-UAV interference ($\alpha_{1,2} \rightarrow \infty$), using the same approach in [11, eq.(11)]. From (8) and (9), it can be seen that the outage probability with joint detector approaches that of an interference-free UAV-2 as $\alpha_{1,2} \rightarrow \infty$. Hence, the joint detector is suitable for strong interference scenarios since the detection of the SOI becomes easier. Although the SIC is also known to perform well at very strong inter-UAV interference levels, the joint detector still outperforms the SIC detector at high SNRs, as shown in Section V. More importantly, (9) also suggests the possibility of the joint detector attaining near-genie-aided, i.e., interference-free, outage performance when interference is sufficiently strong.

B. Benchmark Schemes and System Level Outage Probability

In this work, the II detector, SIC detector, and the HD-UCS are also considered at UAV-2. These schemes are treated as benchmark schemes as the associated outage probability expressions are already available in the literature, with the references provided in Table I. At the GS, residual SI is present and thus, the GS effectively adopts an II detector. The outage probability expression for the GS is also available in the literature and is similarly provided in Table I.

To compare the overall performance of the HBD-UCS against the HD-UCS at the system level, we define the HBD

and HD system level outage probability as:

$$P_{out,system}^\beta = \max \{Pr(O_{gs}^{HBD}), Pr(O_2^\beta)\}, \quad (10)$$

$$P_{out,system}^{HBD} = \max \{Pr(O_{gs}^{HBD}), Pr(O_2^{HBD})\} \quad (11)$$

where $\beta \in \{HBD(II), HBD(SIC), HBD(JD)\}$. The defined HBD system level outage probability enables the identification of performance bottleneck in the proposed HBD-UCS.

IV. FINITE SNR ANALYSIS

In this section, the necessary mathematical preliminaries and closed-form expressions for finite SNR diversity gains are presented for both fixed and variable transmission rate systems, with detailed derivations omitted for brevity.

A. Mathematical Preliminaries

1) *Finite SNR Diversity Gain*: The asymptotic diversity gain of a system, given by Zheng and Tse [34, eq. (3)], quantifies the outage probability decay rate at high SNR. However, the definition in [34, eq. (3)] may not be accurate at low to moderate SNR ranges [20].

To this end, finite SNR diversity gain definitions for low to moderate SNR ranges have been presented by Narasimhan [21, eq. (5)] and Shin et al. [20]. Let O , $Pr(O)$, R , γ and Ω be the outage event, outage probability, transmission rate, threshold and average received power with unit noise variance, respectively. Then, the finite SNR diversity gain (d_f) of a given system is [21, eq. (5)]:

$$d_f = \frac{-\Omega}{Pr(O)} \frac{\partial}{\partial \Omega} Pr(O). \quad (12)$$

At high SNR, (12) is consistent with the asymptotic diversity gain definition given by Zheng and Tse [34], as proven by Shin et al. [20] and Heidarpour et al. [35]. Moreover, (12) enables system designers to investigate the impact of residual SI and inter-UAV interference in HBD-UCS and to quantify potential outage performance improvements through code designs for the II, SIC and joint detectors at typical operating SNR ranges.

2) *Finite SNR DMT Parameters*: For variable transmission rate systems, i.e., adaptive rate systems, the finite SNR multiplexing gain r_f is defined as [21, eq. (4)]:

$$r_f = \frac{R(\Omega)}{\log_2(1 + \Omega)}. \quad (13)$$

In variable transmission rate systems, $Pr(O)$ is computed with respect to $\gamma = (1 + \Omega)^{r_f} - 1$. The finite SNR multiplexing gain indicates the sensitivity of γ when Ω changes, and similar to (12), (13) has also been proven by Shin et al. [20] and Heidarpour et al. [35] to be consistent with asymptotic multiplexing gain in [34, eq. (3)].

Let $\Delta(\Omega) = \hat{\Omega} - \Omega$ where $\hat{\Omega} > \Omega$. Then, extending upon (12), the finite SNR diversity gain for variable transmission rate systems (denoted as d_f^*) is [20, eq. (36)]:

$$d_f^* = \frac{-\Omega}{Pr(O)} \lim_{\Delta(\Omega) \rightarrow 0} \left[\frac{Pr(\hat{O}) - Pr(O)}{\Delta(\Omega)} \right] \quad (14)$$

$$= \frac{-\Omega}{Pr(O)} \frac{\partial}{\partial \Delta(\Omega)} Pr(\hat{O}) \Big|_{\Delta(\Omega)=0}, \quad (15)$$

where (15) is obtained from (14) by applying L'hopital's rule with respect to $\Delta(\Omega)$, $\hat{O}$ is the outage event with respect to $R(\Omega + \Delta(\Omega))$ and $Pr(\hat{O})$ is the outage probability with average received power $\hat{\Omega} = \Omega + \Delta(\Omega)$, threshold $\hat{\gamma} = [1 + \Omega + \Delta(\Omega)]^{r_f} - 1$ and $Pr(\hat{O}) = Pr(O)$ when $\Delta(\Omega) = 0$. Furthermore, although not explicitly shown in (15), we define d_f^* to be non-negative, i.e., $d_f^* = \max \left\{ 0, \frac{-\Omega}{Pr(O)} \frac{\partial}{\partial \Delta(\Omega)} Pr(\hat{O}) \Big|_{\Delta(\Omega)=0} \right\}$, as it is a measure of the negative slope of the outage probability curve [21].

Let the normalized n^{th} moment of a RV Z be:

$$M\{Z^n\} = \frac{E\{Z^n\}}{(\Omega)^n} \quad (16)$$

and let function $g(i, j, \Omega, r_f)$ be:

$$g(i, j, \Omega, r_f) = ([1 + \Omega]^{r_f} - 1)^i (\Omega)^j \left[([1 + \Omega]^{r_f} - 1) \frac{j}{\Omega} + (i + 1)(r_f)(1 + \Omega)^{r_f - 1} \right], \quad (17)$$

where i and j are integers. The function $g(i, j, \Omega, r_f)$ reflects the outage probability decay rate of a variable transmission rate scheme due to average received power (Ω) and finite SNR multiplexing gain (r_f) [11].

It should be noted that the resultant finite SNR diversity gain expression in (15) is based on [20, eq. (36)] and [21, eq. (5)]. Although [20, eq. (36)] and [21, eq. (5)] evaluated finite SNR diversity gain through different approaches and definitions, the former is based on the latter. Hence, (15) shows that both works are unified under the same principles. Similar to (12), the impact of residual SI and inter-UAV interference in adaptive HBD-UCS can be analyzed through (15).

B. Finite SNR Diversity Gain and DMT for HBD Systems

For the joint detector, the finite SNR diversity gain ($d_{f,2}^{HBD(JD)}$) is given in the following proposition.

Proposition 1: The finite SNR diversity gain at UAV-2 for the joint detector is:

$$\begin{aligned} d_{f,2}^{HBD(JD)} &\approx \frac{-\Omega_X}{Pr(O_2^{HBD(JD)})} \left[\sum_{m=0}^{K_{tr}} \bar{\alpha}(m, \alpha_{g,2}, K_{X_{gs}}, \gamma_{th,2}^{HBD}) \right. \\ &\quad \times (-m - 1)(\Omega_X)^{-m-2} + \sum_{n=0}^{K_{tr}} \sum_{i=0}^n \sum_{j=0}^{i+1} \bar{\alpha}(i, \alpha_{1,2}, K_{Y_1}, 1) \\ &\quad \times \bar{\alpha}(n - i, \alpha_{g,2}, K_{X_{gs}}, 1) \binom{i+1}{j} (-1)^{i+1} G_1(i, j, b_2, \gamma_{th,2}^{HBD}) \\ &\quad \left. \times \frac{G_2(j + n - i + 1, b_1, \gamma_{th,2}^{HBD})}{j + n - i + 1} (-n - 2)(\Omega_X)^{-n-3} \right]. \quad (18) \end{aligned}$$

Proof: At UAV-2, $d_{f,2}^{HBD(JD)}$ can be obtained from (9) and (12). ■

The expression in (18) is accurate even at low to moderate Ω_X , and it is useful in evaluating the impact of inter-UAV interference on outage probability decay trends. To uncover the asymptotic outage behavior for the joint detector, we evaluate (18) at high Ω_X , as shown in the following corollary.

Corollary 1: At UAV-2, the joint detector achieves full diversity at high SNR regimes.

Proof: To prove Corollary 1, we have to show that

$$\lim_{\Omega_X \rightarrow \infty} \frac{-\Omega_X}{Pr(O_2^{HBD(JD)})} \frac{\partial}{\partial \Omega_X} Pr(O_2^{HBD(JD)}) = 1. \quad (19)$$

By simplifying (18) and evaluating the limits with respect to Ω_X leads to the following expression:

$$\begin{aligned} \lim_{\Omega_X \rightarrow \infty} d_{f,2}^{HBD(JD)} &\approx \lim_{\Omega_X \rightarrow \infty} \frac{-1}{\Omega_X \cdot Pr(O_2^{HBD(JD)})} \left[\right. \\ &\times \sum_{m=0}^{K_{lr}} \bar{\alpha}(m, \alpha_{g,2}, K_{X_{gs}}, \gamma_{th,2}^{HBD}) (-m-1) (\Omega_X)^{-m} \\ &+ \sum_{n=0}^{K_{lr}} \sum_{i=0}^n \sum_{j=0}^{i+1} \bar{\alpha}(i, \alpha_{1,2}, K_{Y_1}, 1) \bar{\alpha}(n-i, \alpha_{g,2}, K_{X_{gs}}, 1) \binom{i+1}{j} \\ &\times G_1(i, j, b_2, \gamma_{th,2}^{HBD}) \frac{G_2(j+n-i+1, b_1, \gamma_{th,2}^{HBD}) (-n-2)}{(-1)^{-i-1} (j+n-i+1) (\Omega_X)^{n+1}} \left. \right] \quad (20) \end{aligned}$$

For the first term in the numerator of (20), $\lim_{\Omega_X \rightarrow \infty} (\Omega_X)^{-m} = 0$ when $m > 0$ and $\lim_{\Omega_X \rightarrow \infty} (\Omega_X)^{-m} = 1$ when $m = 0$. Likewise for the second term in the numerator, $\lim_{\Omega_X \rightarrow \infty} (\Omega_X)^{-n-1} = 0$ for $n \geq 0$. Therefore, we only consider $m = 0$ when evaluating the limit in the numerator. Repeating the same steps for the denominator in (20) leads to (19) ■

From (19), the joint detector's diversity gain is better than the II and SIC detectors, as shown in [11, eq. (28)], and is equivalent to an HD-UCS [11, eq. (31)].

For the GS and UAV-2 operating under a variable rate transmission scheme, let the variable transmission rate of UAV-1 and GS be $R_1^{HBD}(\Omega_X) = r_{f,1} \log_2(1 + \Omega_X)$ and $R_{gs}^{HBD}(\Omega_X) = r_{f,gs} \log_2(1 + \Omega_X)$, respectively. Also, let the threshold at GS and UAV-2 be $\gamma_{th,gs}^{HBD} = [1 + \Omega_X]^{r_{f,1}} - 1$ and $\gamma_{th,2}^{HBD} = [1 + \Omega_X]^{r_{f,gs}} - 1$, respectively. Then, the variable rate finite SNR diversity gain expressions are presented in the following propositions.

Proposition 2: At GS, the variable rate finite SNR diversity gain is:

$$\begin{aligned} d_{f,gs}^{HBD*} &\approx \frac{-\Omega_X}{Pr(O_{gs}^{HBD})} \sum_{q=0}^{K_{lr}} \sum_{l_1+l_2+l_3=q+1} \bar{\alpha}(q, 1, K_{X_1}, 1) \frac{(q+1)!}{l_1! \cdot l_2! \cdot l_3!} \\ &\times M\{Y_{si,1}^{l_1}\} M\{Y_{si,2}^{l_2}\} g(q, l_1 + l_2 - q - 1, \Omega_X, r_{f,1}). \quad (21) \end{aligned}$$

Proof: Let $\Omega = \Omega_X$, $\hat{\Omega} = \hat{\Omega}_X$ and $\gamma = \gamma_{th,gs}^{HBD} = [1 + \Omega_X]^{r_{f,1}} - 1$ and $O = O_{gs}^{HBD}$. Then, $d_{f,gs}^{HBD*}$ can be obtained through algebraic manipulations by substituting [11, eq. (6)] into (15). ■

Proposition 3: At UAV-2, the variable rate finite SNR diversity gain with the II and the SIC detectors are given in (22) and (23), respectively, at the top of the next page.

Proof: Let $\Omega = \Omega_X$, $\hat{\Omega} = \hat{\Omega}_X$ and $\gamma = \gamma_{th,2}^{HBD} = [1 + \Omega_X]^{r_{f,gs}} - 1$ and $O = O_2^{HBD,i}$, $i \in \{II, SIC\}$. Then, $d_{f,2}^{HBD(II)*}$ and $d_{f,2}^{HBD(SIC)*}$ can be obtained through algebraic manipulations by respectively substituting [11, eq. (8)] and [11, eq. (10)] into (15). ■

TABLE II
REFERENCES FOR THE FINITE SNR DIVERSITY GAINS OF THE BENCHMARK SCHEMES

Protocol/Detector	Notation	Reference
II Detector at GS	$d_{f,gs}^{HBD}$	[11, eq. (24)]
II Detector at UAV-2	$d_{f,2}^{HBD(II)}$	[11, eq. (26)]
SIC Detector at UAV-2	$d_{f,2}^{HBD(SIC)}$	[11, eq. (27)]
HD-UCS at GS	$d_{f,gs}^{HD}$	[11, eq. (29)]
HD-UCS at UAV-2	$d_{f,2}^{HD}$	[11, eq. (30)]

Proposition 4: At UAV-2, the variable rate finite SNR diversity gain for the joint detector is given in (24) at the top of the next page, where:

$$\begin{aligned} G'_1(i, j, b_2, \gamma_{th,2}^{HBD}) &= (i+1-j)(-b_2)^{i-j} (-r_{f,1} + r_{f,gs}) \\ &\times (1 + \Omega_X)^{(r_{f,1} + r_{f,gs})-1} - \frac{j(r_{f,gs})(1 + \Omega_X)^{r_{f,gs}-1}}{(-\gamma_{th,2}^{HBD})^{j+1}} \\ G'_2(j+n-i+1, b_1, \gamma_{th,2}^{HBD}) &= \frac{(-\gamma_{th,2}^{HBD})^{j+1}}{(j+n-i+1)(b_1)^{j+n-i}} \\ &\times [(r_{f,1} + r_{f,gs})(1 + \Omega_X)^{r_{f,1} + r_{f,gs}-1} - r_{f,1}(1 + \Omega_X)^{r_{f,1}-1}] \\ &- (j+n-i+1)(\gamma_{th,2}^{HBD})^{j+n-i} (r_{f,gs}(1 + \Omega_X)^{r_{f,gs}-1}) \end{aligned}$$

It should be pointed out that $G'_1(i, j, b_2, \gamma_{th,2}^{HBD})$ and $G'_2(j+n-i+1, b_1, \gamma_{th,2}^{HBD})$ are the derivative of $G_1(i, j, b_2, \gamma_{th,2}^{HBD})$ and $G_2(j+n-i+1, b_1, \gamma_{th,2}^{HBD})$, respectively.

Proof: Let $b_1 = (1 + \Omega_X)^{r_{f,1} + r_{f,gs}} - (1 + \Omega_X)^{r_{f,1}}$, $b_2 = (1 + \Omega_X)^{r_{f,1} + r_{f,gs}} - 1$, $\Omega = \Omega_X$, $\hat{\Omega} = \hat{\Omega}_X$ and $\gamma = \gamma_{th,2}^{HBD} = [1 + \Omega_X]^{r_{f,gs}} - 1$ and $O = O_2^{HBD(JD)}$. Then, following a similar approach in [11, eq. (35)], $d_{f,2}^{HBD(JD)*}$ is obtained from (15). ■

The finite SNR diversity gain presented earlier enables system designers to quantify the degree of improvement obtainable through an increase in SNR, thus identifying suitable detectors for various inter-UAV interference scenarios.

C. Benchmark Schemes and System Level Finite SNR Diversity Gain

Similar to Section III-B, the diversity gains of the benchmark schemes at the GS and at UAV-2 are available in the literature, with the references provided in Table II. The system level diversity gains are defined as:

$$d_{f,system}^{\beta} = \min \{d_{f,gs}^{HBD}, d_{f,2}^{\beta}\}, \quad (25)$$

$$d_{f,system}^{HD} = \min \{d_{f,gs}^{HD}, d_{f,2}^{HD}\}, \quad (26)$$

$$d_{f,system}^{\beta*} = \min \{d_{f,gs}^{HBD*}, d_{f,2}^{\beta*}\}, \quad (27)$$

$$d_{f,system}^{HD*} = \min \{d_{f,gs}^{HD*}, d_{f,2}^{HD*}\}, \quad (28)$$

where $\beta \in \{HBD(II), HBD(SIC), HBD(JD)\}$. Quantifying the system level diversity gains allows for the identification of supported QoS requirements for the discussed detectors under various inter-UAV interference scenarios, which is discussed in the next section.

V. NUMERICAL AND SIMULATION RESULTS

In this section, we present the numerical and simulation results of the outage probabilities and finite SNR diversity

$$d_{f,2}^{HBD(II)*} \approx \frac{-\Omega_X}{Pr(O_2^{HBD(II)})} \sum_{q=0}^{K_{lr}} \sum_{l=0}^{q+1} \bar{\alpha}(q, \alpha_{g,2}, K_{X_{gs}}, 1) \binom{q+1}{l} M\{Y_1^l\} g(q, l-q-1, \Omega_X, r_{f,gs}). \quad (22)$$

$$d_{f,2}^{HBD(SIC)*} \approx \frac{-\Omega_X}{Pr(O_2^{HBD(SIC)})} \left[\sum_{q=0}^{K_{lr}} \sum_{l=0}^{q+1} \bar{\alpha}(q, \alpha_{1,2}, K_{Y_1}, 1) \binom{q+1}{l} M\{X_{gs}^l\} g(q, l-q-1, \Omega_X, r_{f,1}) + \sum_{m=0}^{K_{lr}} \bar{\alpha}(m, \alpha_{g,2}, K_{X_{gs}}, 1) \right. \\ \left. \times g(m, -m-1, \Omega_X, r_{f,gs}) - \sum_{n=0}^{K_{lr}} \sum_{i=0}^n \sum_{j=0}^{i+1} \bar{\alpha}(i, \alpha_{1,2}, K_{Y_1}, 1) \bar{\alpha}(n-i, \alpha_{g,2}, K_{X_{gs}}, 1) \frac{\binom{i+1}{j}}{j+n-i+1} g(j+n+1, -n-2, \Omega_X, r_{f,1}) \right]. \quad (23)$$

$$d_{f,2}^{HBD(JD)*} \approx \frac{-\Omega_X}{Pr(O_2^{HBD(JD)})} \left[\sum_{m=0}^{K_{lr}} \bar{\alpha}(m, \alpha_{g,2}, K_{X_{gs}}, 1) g(m, -m-1, \Omega_X, r_{f,gs}) + \sum_{n=0}^{K_{lr}} \sum_{i=0}^n \sum_{j=0}^{i+1} \bar{\alpha}(i, \alpha_{1,2}, K_{Y_1}, 1) \right. \\ \left. \times \bar{\alpha}(n-i, \alpha_{g,2}, K_{X_{gs}}, 1) \binom{i+1}{j} \frac{(-1)^{i+1}}{j+n-i+1} \left(G_1(i, j, b_2, \gamma_{th,2}^{HBD}) G_2(j+n-i+1, b_1, \gamma_{th,2}^{HBD}) \frac{-n-2}{(\Omega_X)^{n+3}} \right. \right. \\ \left. \left. + (\Omega_X)^{-n-2} \left[G_1(i, j, b_2, \gamma_{th,2}^{HBD}) G_2'(j+n-i+1, b_1, \gamma_{th,2}^{HBD}) + G_2(j+n-i+1, b_1, \gamma_{th,2}^{HBD}) G_1'(i, j, b_2, \gamma_{th,2}^{HBD}) \right] \right) \right]. \quad (24)$$

gains at UAV-2 and at system level. Monte Carlo simulations, conducted with 10^9 samples, are also presented to verify the accuracy of the outage probability computations of the various detectors. The Rician K factors, i.e., K_{X_1} , $K_{Y_{si,1}}$, $K_{X_{gs}}$, K_{Y_1} , are fixed at 15. The noise variance at GS (σ_g^2) and UAV-2 (σ_2^2) are fixed at -115dBm , with HD sum rate (R_{sum}^{HD}) and HBD sum rate (R_{sum}^{HBD}) set to 1, i.e., $R_{sum}^{HD} = R_{sum}^{HBD} = 1$.

A. Outage and Finite SNR Diversity Gain Analysis at UAV-2

Result 1: The joint detector achieves genie-aided outage performance when inter-UAV interference is sufficiently strong and is not interference-limited at high SNR regimes.

The outage probabilities and diversity gains of the II, SIC, and the joint detectors are plotted in Fig. 3. As a comparison, the outage probability and diversity gain of the HD-UCS are also included. From Fig. 3a, it is observed for all inter-UAV interference levels that the joint detector achieves genie-aided outage probability at moderate and high SNR regimes. However, at very low SNR regimes, a slight performance degradation is observed for the joint detector due to weak inter-UAV interference. Additionally, it is observed that both the II and the SIC detectors are interference-limited at high SNR regimes, unlike the joint detector. Such a behavior is reflected in the intersection of the HBD-UCS outage probability with the HD-UCS in Fig. 3a. Nonetheless, the SIC detector attains lower outage probability than the II detector under strong inter-UAV interference, e.g., $\alpha_{1,2} = 5$. Similarly, the II detector attains lower outage probability than the SIC detector under weak inter-UAV interference, e.g., $\alpha_{1,2} = 0.5$.

In Fig. 3b, the diversity gain expressions of the II, SIC and the joint detectors are validated. As finite SNR diversity gain quantifies the decay of outage probability curves, it can be observed that the diversity gain of the various detectors corresponds to the steepness of the associated outage probability curves in Fig. 3a. Furthermore, the diversity gain of the

joint detector indicates that outage probability can be further improved when Ω_X is increased. It is also shown that the joint detector attains genie-aided diversity gains as $\Omega_X \rightarrow \infty$, validating Corollary 1.

When compared against the HD-UCS, the joint detector achieves much better finite SNR diversity gains at low SNR regimes. However, at moderate SNR regimes, the absence of inter-UAV interference causes the HD-UCS to achieve better diversity gains than the joint detector and the genie-aided HBD-UCS. In particular, the effect of inter-UAV interference on the joint detector's finite SNR diversity gain is reflected in the second term of (18). In the case of HD-UCS, the inter-UAV interference term is absent, thus enabling better diversity gain than the joint detector. Finally, the HD-UCS, joint detector and the genie-aided HBD-UCS achieves the same diversity gains at asymptotic SNR regimes. In contrast, the diversity gain of the II and the SIC detectors approaches 0 as $\Omega_X \rightarrow \infty$ since both detectors are interference-limited at high SNR regimes. Similar to Fig. 3a, the intersection in Fig. 3b indicates the SNR where the decay rate of the HD-UCS is greater than the HBD-UCS. However, it must be noted that a large diversity gain is not an indication of better performance in absolute terms. Instead, it only shows how fast outage probability is decaying as SNR is increasing.

Result 2: The impact of moderate inter-UAV interference on the joint detector is negligible, with lower outage probability observed than the II and the SIC detectors.

It can be observed in Fig. 3a that the SIC detector attains lower outage probability as inter-UAV interference ($\alpha_{1,2}$) is increased. Likewise, the II detector attains lower outage probability as $\alpha_{1,2}$ is decreased. On the contrary, the joint detector is observed to be unaffected by inter-UAV interference and maintains a lower outage probability than the II and the SIC detectors.

From Fig. 3, the II and the SIC detectors are suitable for

(a) Outage probability comparison at UAV-2.

(b) Finite SNR diversity gain comparison at UAV-2.

Fig. 3. Outage probability and finite SNR diversity gain at UAV-2 (II, SIC and joint detectors) for $\alpha_{g,2} = 1$.

TABLE III
SYSTEM LEVEL HBD-UCS PERFORMANCE BOTTLENECK FOR
 $\epsilon \in \{0.01, 0.001\}$

Mode	$\alpha_{1,2}$	$Pr(O_{gs}) \leq Pr(O_2)$	$Pr(O_{gs}) > Pr(O_2)$
HBD(II)	$\alpha_{1,2} \in \{0.5, 0.7\}$	$0dB \leq \Omega_X \leq 30dB$	-
HBD(SIC)	$\alpha_{1,2} = 5$	$4dB < \Omega_X \leq 30dB$	$0dB \leq \Omega_X \leq 4dB$
HBD(SIC)	$\alpha_{1,2} = 7$	$7dB < \Omega_X \leq 30dB$	$0dB \leq \Omega_X \leq 7dB$
HBD(JD)	$\alpha_{1,2} \in \{0.5, 0.7\}$	$0dB \leq \Omega_X < 2dB$	$2dB \leq \Omega_X \leq 30dB$
HBD(JD)	$\alpha_{1,2} \in \{5, 7\}$	-	$0dB \leq \Omega_X \leq 30dB$

weak and strong inter-UAV interference scenarios, respectively. Furthermore, the joint detector attains, either genie-aided or near-genie-aided, outage performance over the II and the SIC detectors in weak, moderate and strong interference scenarios. Therefore, the proposed HBD-UCS with joint detector can achieve superior reliability and is suitable across weak, moderate, and strong inter-UAV interference scenarios.

B. Outage and Finite SNR Diversity Gain Analysis at the System Level

Result 3: At the system level, the HBD-UCS with JD achieves near-genie-aided performance at low SNR regimes. In contrast, SI causes the HBD-UCS with JD to be suboptimal at moderate and high SNR regimes.

The system level outage probability and diversity gain are plotted in Fig. 4 for the HBD-UCS and the HD-UCS. When the II detector is used, the system level performance (outage probability and diversity gain) of the HBD-UCS is constrained by inter-UAV interference. For the SIC detector, the system level performance of the HBD-UCS at low SNR regime is noise-limited. Residual SI is also treated as noise at the FD-enabled GS. Therefore, the GS is the bottleneck at low SNR regimes. When SNR is high, the system level performance is constrained by the inter-UAV interference at UAV-2. For JD, the system level performance of the HBD-UCS is observed to be constrained by residual SI under strong inter-UAV interference ($\alpha_{1,2} \in \{5, 7\}$). For weak inter-UAV

interference, e.g., $\alpha_{1,2} \in \{0.5, 0.7\}$, system level performance is only constrained by $\alpha_{1,2}$ at very low SNR regimes.

When compared against the II and the SIC detectors, the joint detector enables the HBD-UCS to achieve near-genie-aided system level performance at low SNR regimes under weak, moderate and strong inter-UAV interference levels. These observations are validated through numerical simulations and tabulated in Table III.

C. Finite SNR DMT Analysis at UAV-2 and System level

For variable transmission rate schemes, finite SNR DMT curves at UAV-2 are presented in Fig. 5a. At the system level, the HBD finite SNR DMT is plotted in Fig. 5b.

Result 4: As inter-UAV interference increases, the joint detector attains better diversity gain at higher multiplexing gains than the II detector, SIC detector, and HD-UCS at both UAV-2 and system level.

In Fig. 5a, it is shown that the joint detector at UAV-2 attains genie-aided finite SNR diversity gains at low multiplexing gains. At high multiplexing gains, the joint detector attains near-genie-aided finite SNR diversity gains as inter-UAV interference increases. On the other hand, the II and the SIC detectors at UAV-2 are observed to attain lower finite SNR diversity gains than the HD-UCS at low multiplexing gains. Furthermore, only the SIC detector showed better finite SNR diversity gains than the HD-UCS at moderate multiplexing gains, e.g., $0.45 \leq r_f \leq 0.6$. Finally, it is observed that the HD-UCS achieves non-zero diversity gain only up to $r_f = 0.5$ while the joint detector achieves non-zero diversity gains up to twice that of the HD-UCS.

At the system level (Fig. 5b), the finite SNR diversity gain is constrained by residual SI at the FD-enabled GS due to imperfect SI channel estimation (ϵ) for the II, SIC, and the joint detectors. Only the SIC and the joint detectors exhibited better finite SNR diversity gains than the HD-UCS as inter-UAV interference increases for $0.45 \leq r_f \leq 0.65$.

(a) System level outage probability comparison.

(b) System level finite SNR diversity gain comparison.

Fig. 4. System level outage probability and finite SNR diversity gain (II, SIC and joint detectors) for $\alpha_{g,2} = 1$, $\alpha_{g,g} = 1$, $\gamma_{\phi}^2 = -130\text{dBm}$ and $\epsilon \in \{0.01, 0.001\}$.

(a) Finite SNR DMT at UAV-2.

(b) System level finite SNR DMT.

Fig. 5. Finite SNR DMT at UAV-2 and system level (II, SIC and joint detectors) for $\alpha_{g,2} = 1$, $\alpha_{g,g} = 1$, $\gamma_{\phi}^2 = -130\text{dBm}$ and $\Omega_X = 10\text{dB}$.

From Fig. 4, the joint detector enables HBD-UCS to achieve better reliability in multi-UAV networks while attaining higher throughput than existing HD-UCS.

D. Finite SNR Multiplexing Gain Regions at UAV-2

So far, we have assumed that the multiplexing gains of the FD-enabled GS and UAV-1 are the same, i.e., $r_{f,1} = r_{f,g} = r_f$. In contrast, we assume different multiplexing gains for UAV-1 and the GS in the subsequent analysis. The achievable finite SNR diversity gains for the SIC detector ($d_{f,2}^{HBD(SIC)*}$) and the joint detector ($d_{f,2}^{HBD(JD)*}$) are plotted in Fig. 6a and Fig. 6b, respectively. We omit plotting the achievable finite SNR diversity gain of the II detector ($d_{f,2}^{HBD(II)*}$) as the expression is independent of the multiplexing gain of the interference ($r_{f,1}$).

Result 5: The SIC detector achieves non-zero diversity gain when the multiplexing gain of the SOI is larger than the multiplexing gain of the interferer. On the contrary, the achievable diversity gain of the joint detector is independent of the multiplexing gain of the interferer.

From Fig. 6, it is observed that the SIC detector achieves non-zero diversity gain when the multiplexing gain of the SOI is larger than the multiplexing gain of the interferer. As noted in [21], the multiplexing gain of a variable transmission rate scheme determines the impact of Rician K factors on outage decay. In particular, a higher multiplexing gain elicits a stronger influencing effect of the Rician K factor on outage decay and vice versa. The same principle also explains the trend seen in Fig. 6a for the SIC detector. As $r_{f,1}$ increases, the Rician K factor corresponding to the interfering link (K_{Y_1}) starts to affect the overall outage decay of the SIC detector.

Fig. 6. Achievable finite SNR diversity gain of the SIC detector and joint detector at UAV-2 for different multiplexing gains at UAV-1 ($r_{f,1}$) and the GS ($r_{f,gs}$) when $\alpha_{g,2} = 1$, $\alpha_{1,2} = 15$ and $\Omega_X = 10dB$.

Fig. 7. Overlapping finite SNR multiplexing gain regions (MGRs) of the II, SIC and joint detectors at UAV-2 for $\alpha_{g,2} = 1$, $\alpha_{1,2} = \{0.1, 15\}$ and $\Omega_X = 10dB$. (The MGR separation can be smoothen by plotting the regions with very high resolutions.)

Therefore, $r_{f,gs}$ must also increase, i.e., $0 < r_{f,1} < r_{f,gs} < 1$ to offset the influence of K_{Y_1} on the overall outage decay with the Rician K factor corresponding to the SOI link ($K_{X_{gs}}$).

On the contrary, Fig. 6b shows that the achievable diversity gain of the joint detector is independent of the multiplexing gain of the interferer. Therefore, non-zero $d_{f,2}^{HBD(JD)*}$ can be obtained for a wider range of $r_{f,1}$ and $r_{f,gs}$ values compared to the SIC detector. In strong inter-UAV interference scenarios, the joint detector enables the proposed HBD-UCS to accommodate a wider range of data rate requirements compared to the SIC detector. For instance, video streaming capabilities can be deployed on UAV-1 while still meeting the QoS requirements of CNPC links at the FD-enabled GS, even when inter-UAV interference is strong. Hence JD-based HBD-UCS deployment in UAV networks is attractive when the high data rate requirements are met, albeit at the cost of higher computational complexity compared to SIC-based HBD-UCS

³.

Result 6: The joint detector achieves non-zero diversity gain over a larger multiplexing gain region than the II and the SIC detectors under equivalent inter-UAV interference levels.

In Fig. 7a, the multiplexing gain regions (MGRs) of the joint detector and II detector are shown for $\alpha_{1,2} = 0.1$. In particular, the joint detector achieves non-zero $d_{f,2}^{HBD(JD)*}$ in regions *MGR2* and *MGR3* while the II detector achieves non-zero $d_{f,2}^{HBD(II)*}$ in regions *MGR1* and *MGR2*. In *MGR4*, both the joint detector and II detector achieve zero finite SNR diversity gains. Evidently, the joint detector achieves non-zero finite SNR diversity gains over a larger MGR region than the II detector, with $d_{f,2}^{HBD(JD)*} > d_{f,2}^{HBD(II)*}$ in *MGR2*.

In Fig. 7b, the MGRs of the joint detector and SIC detector are shown for $\alpha_{1,2} = 15$. The joint detector achieves non-zero

³The complexity of the joint detector depends on the particular encoding scheme (e.g., Low-density parity-check or turbo codes) and decoding scheme (e.g., bipartite graph-based or trellis-based decoders), interested readers can refer to [17] for more details

$d_{f,2}^{HBD(JD)*}$ in regions *MGR1*, *MGR2* and *MGR3*. The SIC detector achieves non-zero $d_{f,2}^{HBD(SIC)*}$ in regions *MGR2* and *MGR3*. In *MGR4*, both the joint detector and SIC detector achieve zero finite SNR diversity gains.

From Fig. 7b, it can be observed that the joint detector achieves non-zero finite SNR diversity gains over a larger MGR region than the SIC detector. Furthermore, $d_{f,2}^{HBD(JD)*} > d_{f,2}^{HBD(SIC)*}$ in *MGR2*. However, $d_{f,2}^{HBD(JD)*} = d_{f,2}^{HBD(II)*}$ in *MGR3* when $r_{f,gs}$ is high and $r_{f,1}$ is low since the SIC detector is more likely to detect and remove $x_1[r]$. As inter-UAV interference increases, the joint detector can achieve non-zero diversity gain over a large MGR. In other words, the interfering signal can be transmitted at higher data rates as inter-UAV interference increases.

The trends in Fig. 6 and Fig. 7 show that the joint detector enables the proposed HBD-UCS to achieve higher reliability than the II and SIC detectors while meeting a wider range of Quality-of-Service (QoS) requirements. Therefore, the JD-based HBD-UCS is more flexible in responding to changing QoS requirements and exhibits better reliability over II-based and SIC-based HBD-UCS in multi-UAV networks.

VI. CONCLUSION

An HBD-UCS with JD is proposed in this paper as a step towards addressing spectrum scarcity in UAV communications. An innovative approach to deriving closed-form outage probability and finite SNR diversity gain expressions over Rician fading channels is also presented. Through a comprehensive performance analysis, suitable detectors for various inter-UAV interference scenarios are identified. The degree of performance improvements offered by the joint detector over the II and the SIC detectors are also highlighted. It is also observed that the SIC detector achieves non-zero diversity gain when the interfering signal from UAV-1 is transmitted at a lower data rate than the SOI from the FD-enabled GS. However, when inter-UAV interference is sufficiently strong, the joint detector is observed to be independent of the data rate of the interfering signal. An analysis of the MGR for the II, SIC, and the joint detectors is also conducted, where it is shown that the JD-based HBD-UCS can support a wide range of data rate requirements while achieving superior reliability over the II-based and SIC-based HBD-UCS. Work is in progress on evaluating the JD-based HBD-UCS against II-based HBD-UCS, SIC-based HBD-UCS and HD-UCS through stochastic geometry framework. In addition, the impact of Rician K factors on HBD-UCS performance, extending the outage and finite SNR analysis framework for combinations of Rician and Rayleigh fading with imperfect channel estimation, the design of robust and low complexity SIC detectors and joint detectors that considers multiple UAVs and FD-enabled GSs, and beamforming solutions are also being investigated as part of future works.

ACKNOWLEDGMENT

This research is jointly funded by Airbus Singapore Pte Ltd and the Singapore Economic Development Board (EDB).

APPENDIX A PROOF OF (9)

Let the non-centered Chi-squared probability density function (PDF) of the instantaneous received SOI power (X_{gs}) be $f_{X_{gs}}(x) = \frac{K_{X_{gs}}+1}{\Omega_X \alpha_{g,2}} \exp\left(-K_{X_{gs}} - \frac{(K_{X_{gs}}+1)}{\Omega_X \alpha_{g,2}} x\right) I_0\left(2\sqrt{\frac{K_{X_{gs}}(K_{X_{gs}}+1)}{\Omega_X \alpha_{g,2}}} x\right)$, where $I_0(\cdot)$ is the modified Bessel function of the first kind with zero order [33]. Likewise, let $f_{Y_1}(y) = \frac{K_{Y_1}+1}{\Omega_X \alpha_{1,2}} \exp\left(-K_{Y_1} - \frac{(K_{Y_1}+1)}{\Omega_X \alpha_{1,2}} y\right) I_0\left(2\sqrt{\frac{K_{Y_1}(K_{Y_1}+1)}{\Omega_X \alpha_{1,2}}} y\right)$ be the PDF of the instantaneous received interfering signal power (Y_1). Let $Pr(O_{JD}^1)$ and $Pr(O_{JD}^2)$ be outage regions, where O_{JD}^1 and O_{JD}^2 are defined in (6) and (7), respectively. Then, the closed-form outage expression for the joint detector is evaluated as follows [25, eq. (17)]:

$$Pr(O_2^{HBD(JD)}) = \int_0^{\gamma_{th,2}^{HBD}} f_{X_{gs}}(x) dx + \int_{\gamma_{th,2}^{HBD}}^{b_1} \int_{\frac{x}{\gamma_{th,2}^{HBD}} - 1}^{b_2 - x} f_{Y_1}(y) f_{X_{gs}}(x) dy dx. \quad (29)$$

The first term on the RHS of (29) is easily evaluated to be [36, Table I]:

$$\int_0^{\gamma_{th,2}^{HBD}} f_{X_{gs}}(x) dx = 1 - Q_1\left(\sqrt{2K_{X_{gs}}}, \sqrt{\frac{2(K_{X_{gs}}+1)\gamma_{th,2}^{HBD}}{\Omega_X \alpha_{g,2}}}\right), \quad (30)$$

which is valid for all $\frac{K_{Y_1}+1}{\Omega_X \alpha_{1,2}} \gamma_{th,gs}^{HBD} \geq 0$ [31]. To evaluate the second term on the RHS of (29), we first express the PDF of the instantaneous received SOI power ($f_{X_{gs}}(x)$) into a power series as follows [31, eq. (5)]:

$$f_{X_{gs}}(x) \approx \sum_{q=0}^{K_{tr}} (-1)^q \exp(-K_{X_{gs}}) \frac{L_q^{(0)}(K_{X_{gs}})}{q!} \left(\frac{1+K_{X_{gs}}}{\Omega_X \alpha_{g,2}}\right)^{q+1} x^q \approx \sum_{q=0}^{K_{tr}} \hat{d}(q). \quad (31)$$

Likewise, the PDF of the instantaneous received interfering signal power ($f_{Y_1}(y)$) becomes [31, eq. (5)]:

$$f_{Y_1}(y) \approx \sum_{n=0}^{K_{tr}} (-1)^n \exp(-K_{Y_1}) \frac{L_n^{(0)}(K_{Y_1})}{n!} \left(\frac{1+K_{Y_1}}{\Omega_X \alpha_{1,2}}\right)^{n+1} y^n. \quad (32)$$

Let $c(n) = \sum_{k=0}^{n+1} \bar{\alpha}(n, \Omega_X \alpha_{1,2}, K_{Y_1}, 1) \binom{n+1}{k} (-1)^{n+1} [(-b_2)^{n+1-k} - (-\gamma_{th,2}^{HBD})^{-k}] x^k$. Then, the second term on the RHS of (29) becomes [31], [37]:

$$\begin{aligned} & \int_{\gamma_{th,2}^{HBD}}^{b_1} \int_{\frac{x}{\gamma_{th,2}^{HBD}} - 1}^{b_2 - x} f_{Y_1}(y) f_{X_{gs}}(x) dy dx \\ & \approx \int_{\gamma_{th,2}^{HBD}}^{b_1} f_{X_{gs}}(x) \left[\sum_{n=0}^{K_{tr}} \sum_{k=0}^{n+1} \bar{\alpha}(n, \Omega_X \alpha_{1,2}, K_{Y_1}, 1) \binom{n+1}{k} \right. \\ & \quad \left. \times (-1)^{n+1} [(-b_2)^{n+1-k} - (-\gamma_{th,2}^{HBD})^{-k}] x^k \right] dx \quad (33) \end{aligned}$$

$$\approx \int_{\gamma_{th,2}^{HBD}}^{b_1} \left(\sum_{n=0}^{K_{tr}} c(n) \right) \left(\sum_{q=0}^{K_{tr}} \hat{d}(q) \right) dx \quad (34)$$

$$\begin{aligned}
& \approx \int_{\gamma_{th,2}^{HBD}}^{b_1} \sum_{n=0}^{K_{tr}} \sum_{i=0}^n c(i) \hat{d}(n-i) dx \quad (35) \\
& \approx \sum_{n=0}^{K_{tr}} \sum_{i=0}^n \sum_{j=0}^{i+1} \bar{\alpha}(i, \Omega_X \alpha_{1,2}, K_{Y_1}, 1) \\
& \quad \times \bar{\alpha}(n-i, \Omega_X \alpha_{g,2}, K_{X_{gs}}, 1) \binom{i+1}{j} (-1)^{i+1} \\
& \quad \times G_1(i, j, b_2, \gamma_{th,2}^{HBD}) \frac{G_2(j+n-i+1, b_1, \gamma_{th,2}^{HBD})}{j+n-i+1}, \quad (36)
\end{aligned}$$

where $G_1(i, j, b_2, \gamma_{th,2}^{HBD})$ and $G_2(j+n-i+1, b_1, \gamma_{th,2}^{HBD})$ are defined in (9). It should be pointed out that (33) is obtained by interchanging the order of summation and integration, which is valid for $\gamma_{th,2}^{HBD} \leq x \leq b_2$ [31], and (35) is a result of the Cauchy product [32] in (34). Also, $\sum_{q \geq 0} \hat{d}(q)$ in (34) is valid for $K_{X_{gs}} \geq 0$ [31]. Combining (30) and (36) yields the closed-form outage probability expression for $Pr(O_2^{HBD(JD)})$ in (9). This completes the proof.

APPENDIX B

PROOF OF CONVERGENCE RADIUS FOR (9)

We begin by noting that (34) is convergent if $\sum_{n \geq 0} c(n)$ and $\sum_{q \geq 0} \hat{d}(q)$ are absolutely convergent [31], [32]. Starting with $\sum_{n \geq 0} c(n)$, we note that the PDF of the instantaneous received interfering signal power ($f_{Y_1}(y)$) can be expressed into a power series, as given in (32). Also, the term-wise integration of a convergent power series is only valid within the convergence radius [33]. Therefore, it is of importance to verify the convergence of (32). Let $|L_n^{(0)}(K_{Y_1})| \leq \exp\left(\frac{K_{Y_1}}{2}\right)$ [31] and $n! = n\Gamma(n)$ [33], [36], where $\Gamma(\cdot)$ is the Gamma function. Then, (32) becomes:

$$\begin{aligned}
f_{Y_1}(y) &= \sum_{n \geq 0} (-1)^n \frac{\exp(-K_{Y_1}/2)}{n\Gamma(n)} \left(\frac{1 + K_{Y_1}}{\Omega_X \alpha_{1,2}} \right)^{n+1} y^n \\
&= \sum_{n \geq 0} f(n). \quad (37)
\end{aligned}$$

Employing the D'Alembert test, we get:

$$\lim_{n \rightarrow \infty} \frac{|f(n+1)|}{|f(n)|} = \lim_{n \rightarrow \infty} \frac{1}{n} \left(\frac{1 + K_{Y_1}}{\Omega_X \alpha_{1,2}} \right) y = 0. \quad (38)$$

Therefore, (37) has a convergence radius of ∞ , i.e., absolutely convergent, and accordingly, $\sum_{n \geq 0} c(n)$ is also absolutely convergent. The absolute convergence of $\sum_{q \geq 0} \hat{d}(q)$ is proven in the same manner. Thus, (34) and (36), are also absolutely convergent. This completes the proof.

REFERENCES

- [1] T. Andre, K. A. Hummel, A. P. Schoellig, E. Yanmaz, M. Asadpour, C. Bettstetter, P. Grippa, H. Hellwagner, S. Sand, and S. Zhang, "Application-driven design of aerial communication networks," *IEEE Commun. Mag.*, vol. 52, no. 5, pp. 129–137, 2014.
- [2] M. M. Azari, F. Rosas, K.-C. Chen, and S. Pollin, "Ultra reliable uav communication using altitude and cooperation diversity," *IEEE Trans. Commun.*, vol. 66, no. 1, pp. 330–344, 2018.
- [3] L. Xiao, X. Lu, D. Xu, Y. Tang, L. Wang, and W. Zhuang, "Uav relay in vanets against smart jamming with reinforcement learning," *IEEE Trans. Veh. Technol.*, vol. 67, no. 5, pp. 4087–4097, 2018.
- [4] L. Xiao, C. Xie, M. Min, and W. Zhuang, "User-centric view of unmanned aerial vehicle transmission against smart attacks," *IEEE Trans. Veh. Technol.*, vol. 67, no. 4, pp. 3420–3430, 2018.
- [5] J. Wang, C. Jiang, Z. Han, Y. Ren, R. G. Maunder, and L. Hanzo, "Taking drones to the next level: Cooperative distributed unmanned-aerial-vehicular networks for small and mini drones," *IEEE Veh. Technol. Mag.*, vol. 12, no. 3, pp. 73–82, 2017.
- [6] M. Mozaffari, W. Saad, M. Bennis, and M. Debbah, "Wireless communication using unmanned aerial vehicles (uavs): Optimal transport theory for hover time optimization," *IEEE Trans. Wireless Commun.*, 2017.
- [7] D. W. Matolak and R. Sun, "Air-ground channel characterization for unmanned aircraft systems - part iii: The suburban and near-urban environments," *IEEE Trans. Veh. Technol.*, 2017.
- [8] T. Z. H. Ernest, A. Madhukumar, R. P. Sirigina, and A. K. Krishna, "Hybrid-duplex systems for uav communications under rician shadowed fading," in *2018 IEEE 88th Vehicular Technology Conference (VTC Fall)*, Accepted.
- [9] A. Sahai, G. Patel, C. Dick, and A. Sabharwal, "On the impact of phase noise on active cancellation in wireless full-duplex," *IEEE Trans. Veh. Technol.*, vol. 62, no. 9, pp. 4494–4510, 2013.
- [10] E. Tan, R. P. Sirigina, A. K. Krishna, and A. S. Madhukumar, "On the performance analysis of hybrid-duplex systems for aeronautical communications," in *2018 IEEE 87th Vehicular Technology Conference (VTC Spring)*, Accepted.
- [11] E. Z. H. Tan, A. S. Madhukumar, R. P. Sirigina, and A. K. Krishna, "On the outage analysis and finite snr diversity-multiplexing tradeoff of hybrid-duplex systems for aeronautical communications," *arXiv preprint arXiv:1710.09504*, 2017.
- [12] V. S. Annappureddy and V. V. Veeravalli, "Gaussian interference networks: Sum capacity in the low-interference regime and new outer bounds on the capacity region," *IEEE Trans. Inf. Theory*, vol. 55, no. 7, pp. 3032–3050, 2009.
- [13] D. Zahavi and R. Dabora, "On cooperation and interference in the weak interference regime," *IEEE Trans. Inf. Theory*, vol. 63, no. 6, pp. 3894–3922, 2017.
- [14] L. Qu, J. He, and C. Assi, "Understanding the benefits of successive interference cancellation in multi-rate multi-hop wireless networks," *IEEE Trans. Commun.*, vol. 62, no. 7, pp. 2465–2477, 2014.
- [15] S. P. Weber, J. G. Andrews, X. Yang, and G. De Veciana, "Transmission capacity of wireless ad hoc networks with successive interference cancellation," *IEEE Trans. Inf. Theory*, vol. 53, no. 8, pp. 2799–2814, 2007.
- [16] G. Zhou, W. Xu, and G. Bauch, "Is mac joint decoding optimal for interference channels?" in *Proc. Veh. Technol. Conf., Spring 2015*, pp. 1–5.
- [17] I. Shubhi and Y. Sanada, "Joint turbo decoding for overloaded mimo-ofdm systems," *IEEE Trans. Veh. Technol.*, vol. 66, no. 1, pp. 433–442, 2017.
- [18] S. Sharifi, A. K. Tanc, and T. M. Duman, "Ldpc code design for the two-user gaussian multiple access channel," *IEEE Trans. Wireless Commun.*, vol. 15, no. 4, pp. 2833–2844, 2016.
- [19] Y. Zeng, R. Zhang, and T. J. Lim, "Wireless communications with unmanned aerial vehicles: opportunities and challenges," *IEEE Commun. Mag.*, vol. 54, no. 5, pp. 36–42, 2016.
- [20] W.-Y. Shin, S.-Y. Chung, and Y. H. Lee, "Diversity-multiplexing tradeoff and outage performance for rician mimo channels," *IEEE Trans. Inf. Theory*, vol. 54, no. 3, pp. 1186–1196, 2008.
- [21] R. Narasimhan, "Finite-snr diversity-multiplexing tradeoff for correlated rayleigh and rician mimo channels," *IEEE Trans. Inf. Theory*, vol. 52, no. 9, pp. 3965–3979, 2006.
- [22] S. Karmakar and M. K. Varanasi, "The generalized multiplexing gain region of the slow fading mimo interference channel and its achievability with limited feedback," in *Information Theory Proceedings (ISIT), 2012 IEEE International Symposium on*. IEEE, 2012, pp. 3135–3139.
- [23] E. Ahmed and A. M. Eltawil, "All-digital self-interference cancellation technique for full-duplex systems," *IEEE Trans. Wireless Commun.*, vol. 14, no. 7, pp. 3519–3532, 2015.
- [24] N. Zlatanov, E. Sippel, V. Jamali, and R. Schober, "Capacity of the gaussian two-hop full-duplex relay channel with residual self-interference," *IEEE Trans. Commun.*, vol. 65, no. 3, pp. 1005–1021, 2017.
- [25] R. Narasimhan, "Individual outage rate regions for fading multiple access channels," in *Proc. 2007 ISIT*. IEEE, 2007, pp. 1571–1575.
- [26] J. Blomer and N. Jindal, "Transmission capacity of wireless ad hoc networks: Successive interference cancellation vs. joint detection," in *Proc. IEEE Int. Conf. Commun. (ICC)*. IEEE, 2009, pp. 1–5.

- [27] T. Kwon, S. Lim, S. Choi, and D. Hong, "Optimal duplex mode for df relay in terms of the outage probability," *IEEE Trans. Veh. Technol.*, vol. 59, no. 7, pp. 3628–3634, 2010.
- [28] A. Bennatan, S. Shamai, and A. R. Calderbank, "Soft-decoding-based strategies for relay and interference channels: Analysis and achievable rates using ldpc codes," *IEEE Trans. Inf. Theory*, vol. 60, no. 4, pp. 1977–2009, 2014.
- [29] B. Bandemer, A. El Gamal, and Y.-H. Kim, "Simultaneous nonunique decoding is rate-optimal," in *Communication, Control, and Computing (Allerton), 2012 50th Annual Allerton Conference on*. IEEE, 2012, pp. 9–16.
- [30] W. Nam, D. Bai, J. Lee, and I. Kang, "Advanced interference management for 5g cellular networks," *IEEE Commun. Mag.*, vol. 52, no. 5, pp. 52–60, 2014.
- [31] S. Andrs, A. Baricz, and Y. Sun, "The generalized marcum q-function: an orthogonal polynomial approach," *Acta Universitatis Sapientiae Mathematica*, vol. 3, no. 1, pp. 60–76, 2011.
- [32] H. Amann, J. Escher, S. Levy, and M. Cargo, *Analysis*. Springer, 2005, vol. 3.
- [33] I. S. Gradshteyn and I. M. Ryzhik, *Table of integrals, series, and products*. Academic press, 2014.
- [34] L. Zheng and D. N. C. Tse, "Diversity and multiplexing: A fundamental tradeoff in multiple-antenna channels," *IEEE Trans. Inf. Theory*, vol. 49, no. 5, pp. 1073–1096, 2003.
- [35] A. R. Heidarpour, G. K. Kurt, and M. Uysal, "Finite-snr diversity-multiplexing tradeoff for network coded cooperative ofdma systems," *IEEE Trans. Wireless Commun.*, vol. 16, no. 3, pp. 1385–1396, 2017.
- [36] N. B. Rached, A. Kammoun, M.-S. Alouini, and R. Tempone, "A unified moment-based approach for the evaluation of the outage probability with noise and interference," *IEEE Trans. Wireless Commun.*, vol. 16, no. 2, pp. 1012–1023, 2017.
- [37] A. Bartoszewicz and S. Glgb, "Algebrability of conditionally convergent series with cauchy product," *Journal of Mathematical Analysis and Applications*, vol. 385, no. 2, pp. 693–697, 2012.

Rajendra Prasad Sirigina received the B.Tech. degree in Electronics and Communications Engineering from the Gokaraju Rangaraju Institute of Engineering and Technology, Jawaharlal Nehru Technological University, Hyderabad, India, in 2002, the M.Tech. degree in Signal Processing from the Indian Institute of Technology Guwahati, Guwahati, India, in 2007, and the Ph.D. degree from the School of Computer Engineering (SCE), Nanyang Technological University (NTU), Singapore, in 2015.

He is currently a Research Fellow with the School of Computer Science and Engineering, NTU, Singapore. He was a Lecturer for three years in Hyderabad, India. He taught courses related to communication theory for undergraduate students. He was a Deputy Manager with the Reliance Technology Innovation Center, Reliance Communications, Navimumbai, India, for two years. He was also a Research Associate with NTU for approximately two years. His current research interest focuses on interference management in 5G and satellite networks.

Tan Zheng Hui Ernest received the B.Eng in Computer Engineering (First Class Honours) from Nanyang Technological University (NTU) in 2015. He is currently a Research Engineer with Airbus Singapore Private Limited and is working towards his Ph.D degree in Computer Engineering at NTU. His current research interest focuses on the evaluation of interference management in aeronautical communications and performance analysis of unmanned aerial vehicle communications in fifth generation (5G) networks.

Anoop Kumar Krishna completed his Ph.D. in electronics and communication engineering in 1996, from National Institute of Technology (NIT) Tiruchirappalli, India. He obtained his M.Tech. in digital electronics in 1989, from Cochin University of Science and Technology, India and M.Sc. in Physics with Specialization in Applied Electronics in 1986, from University of Kerala, India. He has also completed a Graduate Certificate in Intellectual Property (GCIP) from the National University of Singapore in May 2007. He has over 25 years of experience in

Industry and Academics. He joined Airbus in July 2007 in their Research and Technology Centre, Singapore. He has worked on various wireless and wired communication systems and technology development for different business units of Airbus, including various collaborative research projects with different research institutes and universities. Presently he is leading the R&T activities in the Skyways project. He is a senior IEEE member since 2003. He has also served as TPC member for various conferences and as a reviewer for Journal and conference articles. He has about 50 research publications in journals and conferences of international repute and in the form of granted patents.

A. S. Madhukumar (M'96-SM'02) received the B Tech from the College of Engineering, Trivandrum, India, the M Tech from the Cochin University of Science and Technology, Cochin, India, and the Ph D from the Indian Institute of Technology Madras, Chennai, India.

He is currently an Associate Professor with the School of Computer Science and Engineering, Nanyang Technological University, Singapore. He was involved in communications and signal processing research with the Centre for Development of Advanced Computing, Government of India, and Institute for Infocomm Research (previously known as the Centre for Wireless Communications), Singapore. His current research interests include heterogeneous networks, cooperative radio systems for mobile multihop networks, algorithms and architectures of cognitive radios, new modulation and multiple access schemes, and advanced signal processing algorithms for communication systems. He is involved in a number of funded research projects, organizing international conferences, and a permanent reviewer for many internationally reputed journals and conferences. He has authored or coauthored more than 250 referred international conference and journal papers.