Security and Reliability Performance of a Cooperative Network with Self-Sustaining Nodes

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***Index Terms*—Energy harvesting (EH), physical-layer security (PLS), selective decode and forward (SDF), incremental decode and forward (IDF), security-reliability trade-off (SRT).**

I. Introduction

Internet of things (IoT) is crucial technology in realizing a connected world with sensors embedded in homes, cities and manufacturing plants [2]. 5G and 6G networks will provide network connectivity to these IoT devices besides traditional cellular connectivity. One of the key requirements of 6G network is to support connectivity to 10's of millions of internet of things (IoT) or machine-type devices (MTD) per square kilometer [3]. Therefore, conventional battery charging techniques and replacement are not practical. They may not even be feasible in some scenarios (on-body sensors and in-body implants in biomedical applications for example). Further, devices without batteries have smaller form factor and are cheaper. Such nodes will have to be self-sustaining and use only the harvested energy to remain active. Hence, self-sustaining and battery-less IoT devices which harvest energy from RF signals will play a significant role in 6G [4]. Additionally, relays have been incorporated into communication standards (LTE-Advanced) due to their promise to improve both the reliability and range of the communication network [5], they are especially important in self-sustaining networks since the large variations in the link signal-to-noise (SNR) ratio greatly limit the quality of service (QoS) that can be attained. Consequently, cooperative communication links with EH self-sustaining nodes are important for enhancing energy efficiency, reliability, and range of wireless-powered cooperative communication networks (WPCCN).

Due to the broadcast nature of the wireless medium, communication is susceptible to eavesdropping by illegitimate receivers. Traditional security approaches employing cryptographic algorithms and key management techniques are computationally intensive and unsuited for low-power IoT devices. Recently, physical-layer security (PLS) techniques [6] have been proposed to overcome security issues using the physical characteristics of the channel without using an encryption key. In seminal work by Wyner [7] showed that secrecy is attainable when the eavesdropper channel is a degraded version of the main channel without using key-based encryption. The core idea is that exploiting channel characteristics can enhance physical layer secrecy by enhancing the strength of the main channel over the eavesdropping channel. For powered nodes, the use of cooperative relays in increasing the secrecy of communication networks is now well investigated due its susceptibility to eavesdropping attacks [8]. It is apparent that understanding the secrecy performance of WPCCN with EH nodes is quite different from that of powered nodes, and needs to be studied for use in next-generation networks.

A. Related Works

Recently, PLS of WPCCNs has been of interest to researchers for the meeting requirements of future networks. Cooperative jamming (CJ) is one of the techniques to degrade the eavesdropper channel. In CJ, a friendly node (source or destination) sends a jamming signal to confound the eavesdropper while replenishing energy at the relay node. In destination-based CJ [9]–[12], the source sends an information signal to the relay, and simultaneously destination sends a jamming signal to confound eavesdropper and replenishing energy at the relay. The relay then forwards the information signal with the jamming signal. The destination can cancel the jamming signal known to it while the eavesdropper cannot. In [9], [10] artificial noise (AN) is transmitted by the destination to enable EH (using either time-switching (TS) or power-splitting (PS)) at the amplify-

The authors are with the Department of Electrical Engineering, Indian Institute of Technology (IIT Delhi), New Delhi 110016, India (E-mail: {amit.patel, shankar}@ee.iitd.ac.in). A conference version of this paper restricted only to analysis for SDF is accepted for presentation in IEEE VTC Spring 2023 [1]. In the journal version, we extend the analysis to IDF, discuss power backoff, and compare the performance with SDF. This work was supported by Prof. G.K. Chandramani Chair, IIT Delhi.

TABLE I: Comparison of literature on Cooperative Jamming, Artificial noise, Relay/Jammer selection, Destination assisted Jamming and our work.

	Method of Secrecy	EH Nodes	EH Technique	EH Source
[9]	Destination-based CJ	Relay	SWIPT	Destination jamming signal
[10]–[12]	Destination-based CJ	Relay	SWIPT	Destination jamming and source signal
[13]	Source based jamming	Relay	SWIPT	Source signal
[14]–[17]	Relay based Jamming	Multiple Relays	SWIPT	Source signal
[18]	Intermediate node Jamming	Multiple intermediate nodes	SWIPT	Source signal
[19]	Cooperative Jamming	Multiple DF relays	SWIPT	Power Beacon
Our Work	Power control	Both Source and Relay	PB-WPCN	Power Beacon

and-forward (AF) relay. In [11] both destination jamming noise and the source signal are used to harvest energy at the relay. In [12] the authors study optimal power allocation for jamming and information symbols in an EH AF relay.

Source-based CJ is also well investigated for enhancing energy harvesting at intermediate node while jamming eavesdropper [13]–[16]. In [13] the authors use a fraction of the source power for jamming and the rest for information transmission with the aid of an untrusted EH AF relay. In [14], secrecy is studied with multiple EH AF relays, each harvesting energy from the source signal, and using it for both signal transmission and jamming. A beamforming vector at the relays is determined optimally to maximize the achievable secrecy rate. In [15], the secrecy performance of a cooperative network with intermediate EH nodes (each having finite storage) is studied. Each node acts as a relay for information transmission as well as a jammer. Using energy accumulation and storage information at the nodes, secrecy improvement is achieved. In [16], multi-antenna EH nodes harvest energy from the source signal, with nodes acting as either relays or jammers based on their decoding status. The authors propose a secure beamforming scheme for selected relays to enhance secrecy with both TS and PS at the relay. In [17], [18], uses best node selection, among multiple EH intermediate nodes, for information transmission and rest as jammers to enhance secrecy.

To enable the energy harvesting process at the relay node, simultaneous wireless information and power transfer (SWIPT) was proposed in [20], [21]. In [22], [23] power splitting (PS) and time-switching (TS) protocols were used to harvest energy from jamming signal. Several works studying secrecy with SWIPT have been reported in literature [9]–[16]. Very few works considering wireless-powered communication network (WPCN) architecture (using energy harvesting at nodes) have been reported in literature. SWIPT based EH architecture is suitable only over short ranges, and to overcome this problem [24] have proposed a power beacon (PB) based architecture. Also, PBs do not require any back haul links, hence deployment cost is small [25].

B. Motivation and Contribution

Most of the aforementioned works on WPCCN have the following limitations:

- The assumption of CSI at the source might not be practical considering deployment of millions of nodes in future networks. Since nodes are energy constrained, attaining CSI at the source, for large number of nodes, in each signaling interval is energy expensive.
- Most of the earlier works assume that either the source, relay or jammer (in case of cooperative jamming) is of EH type, and the remaining nodes are powered. With rapidly increasing number of MTDs, all nodes in a communication network are likely to be of the EH type. In a practical scenario, IoT nodes need to assist a distant node to meet its QoS requirements or to assist as a relay for extending the range of communication. Hence understanding the performance of cooperative networks consisting solely of energy harvesting (EH) nodes is very important. The secrecy performance of networks with self-sustaining nodes has never been analyzed with practical nonlinear EH circuits to date.

The only work to consider networks with solely EH nodes is [19], which analyzes the secrecy performance of a two-hop network with PB-based EH at the source and the relay without a direct link. Due to the random nature of the harvested energy, EH nodes need to be close to each other to ensure acceptable QoS. Thus, neglecting the direct link is not always reasonable. Therefore, we assume the presence of direct links to both the destination and the eavesdropper in our system model. In addition, [19] considers the availability of channel knowledge to the destination at both the source and the relays, which is quite difficult in deployment scenarios with such low-power MTDs. In contrast to these assumptions, we assume no channel knowledge both at the source and the relay. Consequently, we assume that the source uses fixed-rate signaling instead. Since the signal-to-noise ratio (SNR) of each link with an energy harvesting source takes the form of the product of exponential random variables, the variance of SNR is large as compared to its mean. For this reason, to ensure good performance, we assume optimal combining of the direct and relayed signals at both the destination and the eavesdropper. This makes analysis of performance quite involved. *In this paper, we study method of power backoff control for secrecy improvement at the expense of throughput performance without any jamming. Also, we show that the position of eavesdropper with respect to source and relay plays an important role in power backoff control for secrecy improvement. The significant contributions of our work are as follows.*

- *We consider both non-incremental and incremental signaling, and establish the superiority of the latter* *in terms of secrecy. Assuming practical nonlinear EH circuits, we obtain an approximate expressions for secrecy outage probability of the multi-antenna system with non-linear EH model for both IDF and SDF relaying schemes assuming fixed-rate transmission.*

- *For a PB-based WPCN, we show that IDF relaying has better secrecy performance than the SDF relaying scheme. Further, we obtain a accurate approximate expression for the secrecy outage in the single antenna scenario. We then establish convexity of transmit power of PB with secrecy outage, suggesting an optimal operating power of network.*
- *We further suggest an novel power control (backoff) strategy at the source and the relay to improve secrecy outage both for IDF and SDF signaling. We then specify the power back-off at both the source and the relay based on different network operating characteristics.*
- *We establish the security-reliability trade-off (SRT) and show that improvement in secrecy is achieved only at the expense of degradation in outage performance. We then demonstrate how the power back-off at the source and/or relay can be used to implement this trade-off.*

The rest of this paper is structured as follows. Section II elaborates on the system model of the PB-assisted cooperative network. Section III analyzes the secrecy performance of the proposed system model. Section IV discusses secrecy improvement through power back-off and SRT of the proposed network. Numerical results based on the mathematical analysis are compared to computer simulations in Section VI. Finally, Section VII concludes the paper.

Notations: $X \sim \mathcal{CN}(\mu,\sigma^2)$ implies that X is a complex normal random variable of mean μ and variance σ^2. $\Pr\{A\}$ denotes the probability of an event A. $f_X(x)$ denotes the probability density function (PDF) of a random variable X. $I_1(\cdot)$ is the modified Bessel function of the first kind (and order 1), $K_1(\cdot)$ denotes the modified Bessel function of the second kind (and order 1), and $E_1(\cdot)$ denotes the exponential integral of type 1. $A \cup B$ and $A \cap B$ respectively denote the union and intersection of events A and B. $\bar{A}$ is the complement of the event A.

II. System Model

Consider a two-hop cooperative network depicted in Fig.1a consisting of a power beacon B, an EH source S, an EH decode-and-forward (DF) relay R, a destination D, and an eavesdropper E. We assume that B, D and E are equipped with M, N and L antennas respectively. We assume a single antenna at the source and the relay. It is assumed that the power beacon B transmits with power P on a sub-carrier to enable EH. Both S and R have no embedded power supply - they harvest energy from B and use it for signaling in another sub-carrier. However, due to the EH half-duplex constraint (the nodes cannot harvest and use the energy concurrently), two super-capacitors are used. While the secondary super-capacitor charges, energy is drawn from the primary super-capacitor for signal transmission. After the signalling period, energy is transferred from the secondary to the primary super-capacitor in a negligible amount of time [26]. The destination D can be either battery-operated or an EH node. Fig.1b depicts the signalling and energy harvesting periods for S and R in a signaling interval T.

Let d_{ij} denote the distance between nodes with $i \in [B,S,R]$ and $j \in [S,R,D,E]$. The path loss between any two nodes i and j is assumed to be $k_{ij} = K(d_0/d_{ij})^m$, where d_0 is the reference distance in the antenna far-field, m is the path loss exponent, $K = (\lambda/(4\pi d_0))^2$ is the free-space path loss at distance d_0, and λ is the wavelength. Denote by B_i, D_j and E_k the i^{th}, j^{th} and k^{th} antenna of B, D and E. We denote by $h_{ab} \sim \mathcal{CN}(0,1)$ the channel between $a \in [B_i,S,R]$ and $b \in [D_j,E_k]$. As in [9], [14], [19], all channels are assumed to be of the Rayleigh fading type. Let $\mathbf{h}_{BS} = [h_{B_1S},\ldots,h_{B_MS}]^T$, $\mathbf{h}_{BR} = [h_{B_1R},\ldots,h_{B_MR}]^T$, $\mathbf{h}_{SD} = [h_{SD_1},\ldots,h_{SD_N}]^T$, $\mathbf{h}_{RD} = [h_{RE_1},\ldots,h_{RE_L}]^T$, $\mathbf{h}_{SE} = [h_{SE_1},\ldots,h_{SE_L}]^T$, and $\mathbf{h}_{RE} = [h_{RE_1},\ldots,h_{RE_L}]^T$.

Power beacon B transmits unit-energy symbols x with power P using maximal ratio transmission (MRT) with weights $\phi_{BS} = \mathbf{h}_{BS}/\parallel \mathbf{h}_{BS} \parallel$ for the first $T/2$ duration, and with weights $\phi_{BR} = \mathbf{h}_{BR}/\parallel \mathbf{h}_{BR} \parallel$ for the next $T/2$ duration. The received signal samples at S and R after matched filtering are

$$y_{BS} = \sqrt{k_{BS}P}\phi_{BS}^H\mathbf{h}_{BS}x + w_{BS}, \text{ and } y_{BR} = \sqrt{k_{BR}P}\phi_{BR}^H\mathbf{h}_{BR}x + w_{BR}, \quad (1)$$

where $w_{BS}, w_{BR} \sim \mathcal{CN}(0,N_o)$ constitute additive white Gaussian noise samples, and $\mathbb{E}(|x|^2) = 1$ ($\mathbb{E}(.)$ is the expectation operator). We consider the non-linear energy harvesting (EH) model [27] with saturation characteristics in energy harvesting circuit. So the harvested power in a signalling interval for non-linear EH at S and R can be expressed as

$$P_S = \begin{cases} \eta P \parallel \mathbf{h}_{BS} \parallel^2 k_{BS}, & \eta P \parallel \mathbf{h}_{BS} \parallel^2 k_{BS} < P_{sat} \\ P_{sat}, & \text{otherwise}, \end{cases} \quad (2)$$

$$P_R = \begin{cases} \eta P \parallel \mathbf{h}_{BR} \parallel^2 k_{BR}, & \eta P \parallel \mathbf{h}_{BR} \parallel^2 k_{BR} < P_{sat} \\ P_{sat}, & \text{otherwise}, \end{cases} \quad (3)$$

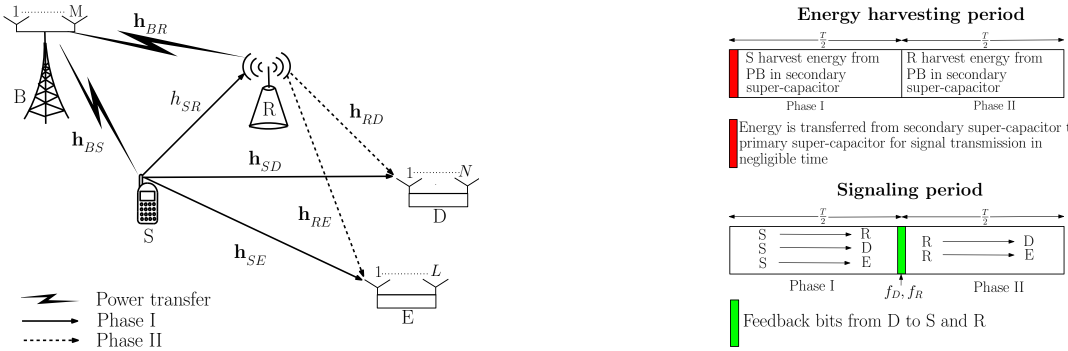
where η is energy harvesting circuit conversion efficiency. We first discuss the case of direct transmission, which is a benchmark scheme.

A. Direct Transmission (DT)

In the case of direct transmission, S transmits unit-energy symbols s at fixed information rate R_t and power P_S in a signaling interval to the destination D, which uses maximal ratio combining (MRC) beamforming vector $\phi_{SD} = \frac{\mathbf{h}_{SD}}{||\mathbf{h}_{SD}||}$ for receiving information. Similarly E uses maximal ratio combining (MRC) beamforming vector $\phi_{SE} = \frac{\mathbf{h}_{SE}}{||\mathbf{h}_{SE}||}$. Then the received signals y_{SD}^{DT} and y_{SE}^{DT} at D and E in a signaling interval are given respectively by

$$y_{SD}^{DT} = \sqrt{k_{SD}P_S}\phi_{SD}^H\mathbf{h}_{SD}s + w_{SD}, \text{ and } y_{SE}^{DT} = \sqrt{k_{SE}P_S}\phi_{SE}^H\mathbf{h}_{SE}s + w_{SE}, (4)$$

where $w_{SD}, w_{SE} \sim \mathcal{CN}(0,N_o)$ constitute additive white Gaussian noise samples. The maximum mutual information between S to D and S to E, normalized with bandwidth, are [28]



(a) (b)

Fig. 1: (a) System model. (b) Energy harvesting and signaling period.

$$I_{SD}^{DT} = \begin{cases} \log_2\left(1+\frac{P\eta k_{BS}k_{SD}g_{BS}g_{SD}}{N_o}\right), & g_{BS} < P_{sat}/P\eta k_{BS} \\ \log_2\left(1+\frac{P_{sat}k_{SD}g_{SD}}{N_o}\right), & \text{otherwise}, \end{cases} \quad (5)$$

$$I_{SE}^{DT} = \begin{cases} \log_2\left(1+\frac{P\eta k_{BS}k_{SE}g_{BS}g_{SE}}{N_o}\right), & g_{BS} < P_{sat}/P\eta k_{BS} \\ \log_2\left(1+\frac{P_{sat}k_{SE}g_{SE}}{N_o}\right), & \text{otherwise}, \end{cases} \quad (6)$$

where $g_{BS} = \| \mathbf{h}_{BS} \|^2$, $g_{SD} = \| \mathbf{h}_{SD} \|^2$, $g_{SR} = |h_{SR}|^2$, and $g_{SE} = \| \mathbf{h}_{SE} \|^2$. The channel gains between nodes S-D and S-E (denoted by g_{SD} and g_{SE} respectively) are exponentially distributed. Clearly, $g_{RD} = \| \mathbf{h}_{RD} \|^2$ and $g_{RE} = \| \mathbf{h}_{RE} \|^2$ are Gamma distributed.

B. Cooperative Transmission

In the case of cooperative transmission, signaling takes place in two phases. Signaling in these phases is described below.

Phase I Signalling

In the first phase (phase I) of signaling, S transmits unit-energy symbols s of information rate R_t with power P_S in a signaling interval to R and D. For reasons that will become apparent later, only a fraction β_S of the available power at S is used for transmission, which implies that S transmit power is $\beta_S P_S$ (we will show later that $\beta_S < 1$ can improve secrecy performance in certain scenarios, or implement the SRT). D uses maximal ratio combining (MRC) beamforming vector $\phi_{SD} = \frac{\mathbf{h}_{SD}}{\|\mathbf{h}_{SD}\|}$ to receive information. Similarly E uses maximal ratio combining (MRC) beamforming vector $\phi_{SE} = \frac{\mathbf{h}_{SE}}{\|\mathbf{h}_{SE}\|}$. In what follows, we use superscripts I and II to distinguish between first and second-phase quantities when required. Then the received signal samples y_{SR}^I, y_{SD}^I and y_{SE}^I at R, D and E respectively in phase I of a signaling interval are given by

$$y_{SR}^I = \sqrt{k_{SR}\beta_S P_S}h_{SR}s + w_{SR}, \quad y_{SD}^I = \sqrt{k_{SD}\beta_S P_S}\phi_{SD}^H\mathbf{h}_{SD}s + w_{SD}, \quad (7)$$

$$\text{and } y_{SE}^I = \sqrt{k_{SE}\beta_S P_S}\phi_{SE}^H\mathbf{h}_{SE}s + w_{SE}, \quad (8)$$

where $w_{SD}, w_{SR}, w_{SE} \sim \mathcal{CN}(0, N_o)$ are additive white Gaussian noise samples. The The maximum mutual information during phase I of signalling between S-R link is

$$I_{SR} = \begin{cases} \log_2\left(1+\frac{\beta_S P\eta k_{BS}k_{SR}g_{BS}g_{SR}}{N_o}\right), & g_{BS} < \frac{P_{sat}}{P\eta k_{BS}} \\ \log_2\left(1+\frac{\beta_S P_{sat}k_{SR}g_{SR}}{N_o}\right), & \text{otherwise} \end{cases}. \quad (9)$$

Further, the maximum mutual information in phase I of signaling between S-D and S-E links are

$$I_{SD} = \begin{cases} \log_2\left(1+\frac{\beta_S P\eta k_{BS}k_{SD}g_{BS}g_{SD}}{N_o}\right), & g_{BS} < \frac{P_{sat}}{P\eta k_{BS}} \\ \log_2\left(1+\frac{\beta_S P_{sat}k_{SD}g_{SD}}{N_o}\right), & \text{otherwise}, \end{cases} \quad (10)$$

$$I_{SE} = \begin{cases} \log_2\left(1+\frac{\beta_S P\eta k_{BS}k_{SE}g_{BS}g_{SE}}{N_o}\right), & g_{BS} < \frac{P_{sat}}{P\eta k_{BS}} \\ \log_2\left(1+\frac{\beta_S P_{sat}k_{SE}g_{SE}}{N_o}\right), & \text{otherwise}. \end{cases} \quad (11)$$

In what follows, we describe phase II signaling with SDF and IDF schemes.

Phase II signaling

Both R and D attempt to decode the information symbols. In case of SDF signaling, R re-encodes and transmits the symbols in the second phase of signaling when decoding is successful in phase I, and D combines the signals in the first and second phases optimally. R is assumed to use a fraction β_R of the available power and transmit with power $\beta_R P_R$ (once again, the reason for this power back-off will become apparent later). When R fails to decode information in phase I, it does not perform relaying in phase II. In case of IDF, signaling depends on decision made by S based on feedback bits from R and D. Specifically, R transmits $f_R = 1$ if it can decode the symbols, and $f_R = 0$ otherwise. Similarly, D communicates feedback bit $f_D = 1$ if decoding is successful, and $f_D = 0$ otherwise. When $f_D = 1$ ($f_R = 1$ or $f_R = 0$), there is no second phase. Instead, new information symbols are transmitted by the source (which clearly increases throughput). Note that information rates at D and E are given by (10). However, if $f_D = 0$ and $f_R = 1$, R transmits the decoded information symbols in the second phase. D uses maximal ratio combining (MRC) beamforming vector $\phi_{RD} = \frac{\mathbf{h}_{RD}}{\|\mathbf{h}_{RD}\|}$ to receiving information. Similarly E uses maximal ratio combining (MRC) beamforming vector $\phi_{RE} = \frac{\mathbf{h}_{RE}}{\|\mathbf{h}_{RE}\|}$. The received signal samples y_{RD}^{II}, y_{RE}^{II} at D and E respectively in phase II of a signaling interval are given by

$$y_{RD}^{II} = \sqrt{k_{RD}\beta_R P_R}\phi_{RD}^H\mathbf{h}_{RD}s + w_{RD}, \; y_{RE}^{II} = \sqrt{k_{RE}\beta_R P_R}\phi_{RE}^H\mathbf{h}_{RE}s + w_{RE}, \quad (12)$$

where $w_{RD}, w_{RE} \sim \mathcal{CN}(0, N_o)$ constitute additive white Gaussian noise samples. The channel gains denoted by $g_{BR} = \| \mathbf{h}_{BR} \|^2$, $g_{RD} = \| \mathbf{h}_{RD} \|^2$, and $g_{RE} = \| \mathbf{h}_{RE} \|^2$ are Gamma distributed. The maximum mutual information during phase II of R-D and R-E links are

$$I_{RD} = \begin{cases} \log_2\left(1+\frac{\beta_R P\eta k_{BR}k_{RD}g_{BR}g_{RD}}{N_o}\right), & g_{BR} < \frac{P_{sat}}{P\eta k_{BR}} \\ \log_2\left(1+\frac{\beta_R P_{sat}k_{RD}g_{RD}}{N_o}\right), & \text{otherwise}, \end{cases} \quad (13)$$

$$I_{RE} = \begin{cases} \log_2\left(1+\frac{\beta_R P\eta k_{BR} k_{RE} g_{BR} g_{RE}}{N_o}\right), & g_{BR} < \frac{P_{sat}}{P\eta k_{BR}} \\ \log_2\left(1+\frac{\beta_R P_{sat} k_{RE} g_{RE}}{N_o}\right), & \text{otherwise}, \end{cases} \tag{14}$$

Further, in case of IDF signaling, when $f_R = f_D = 0$, the signaling to D is in an outage, and the information rates to D and E are once again given by (10). Here we make the worst-case assumption that the eavesdropper monitors the feedback bits f_R and f_D in order to perform optimal combining to maximize its SNR when $f_D = 0$ and $f_R = 1$. In other scenarios, when $f_D = 1$ (direct link is successful), as well as when $f_D = f_R = 0$ (the direct link fails and R fails to decode), E cannot clearly perform combining due to non-availability of the relayed signal in phase II. Due to the independence of the S-D and S-E links, incremental signaling can intuitively be expected to provide a better trade-off between secrecy and throughput.

Due to the small and random nature of harvested energy, the received SNR at the destination is sometimes very low. Optimal combining of direct signal and relayed signal by maximal ratio combining [29] results in improved throughput (and secrecy performance, as we show in this paper). These optimal weights are determined by S-D and R-D channel knowledge at the destination. Hence the SNR at the destination becomes $\Gamma^{I}_{SD} + \Gamma^{II}_{RD}$. Similarly, E also applies the optimal combining of relayed and direct signals to maximize its SNR. So the SNRs Γ_D and Γ_E at D and E after phase II of the signaling interval are given by

$$\Gamma_D = \begin{cases} \frac{\beta_S P\eta k_{BS} k_{SD} g_{BS} g_{SD}}{N_o} + \frac{\beta_R P\eta k_{BR} k_{RD} g_{BR} g_{RD}}{N_o}, & g_{BS} < \frac{P_{sat}}{P\eta k_{BS}}, g_{BR} < \frac{P_{sat}}{P\eta k_{BR}} \\ \frac{\beta_S P\eta k_{BS} k_{SD} g_{BS} g_{SD}}{N_o} + \frac{\beta_R P_{sat} k_{RD} g_{RD}}{N_o}, & g_{BS} < \frac{P_{sat}}{P\eta k_{BS}}, g_{BR} \geq \frac{P_{sat}}{P\eta k_{BR}} \\ \frac{\beta_S P_{sat} k_{SD} g_{SD}}{N_o} + \frac{\beta_R P\eta k_{BR} k_{RD} g_{BR} g_{RD}}{N_o}, & g_{BS} \geq \frac{P_{sat}}{P\eta k_{BS}}, g_{BR} < \frac{P_{sat}}{P\eta k_{BR}} \\ \frac{\beta_S P_{sat} k_{SD} g_{SD}}{N_o} + \frac{\beta_R P_{sat} k_{RD} g_{RD}}{N_o}, & g_{BS} \geq \frac{P_{sat}}{P\eta k_{BS}}, g_{BR} \geq \frac{P_{sat}}{P\eta k_{BR}} \end{cases}. \tag{15}$$

Similarly, SNR at E would be

$$\Gamma_E = \begin{cases} \frac{\beta_S P\eta k_{BS} k_{SE} g_{BS} g_{SE}}{N_o} + \frac{\beta_R P\eta k_{BR} k_{RE} g_{BR} g_{RE}}{N_o}, & g_{BS} < \frac{P_{sat}}{P\eta k_{BS}}, g_{BR} < \frac{P_{sat}}{P\eta k_{BR}} \\ \frac{\beta_S P\eta k_{BS} k_{SE} g_{BS} g_{SE}}{N_o} + \frac{\beta_R P_{sat} k_{RE} g_{RE}}{N_o}, & g_{BS} < \frac{P_{sat}}{P\eta k_{BS}}, g_{BR} \geq \frac{P_{sat}}{P\eta k_{BR}} \\ \frac{\beta_S P_{sat} k_{SE} g_{SE}}{N_o} + \frac{\beta_R P\eta k_{BR} k_{RE} g_{BR} g_{RE}}{N_o}, & g_{BS} \geq \frac{P_{sat}}{P\eta k_{BS}}, g_{BR} < \frac{P_{sat}}{P\eta k_{BR}} \\ \frac{\beta_S P_{sat} k_{SE} g_{SE}}{N_o} + \frac{\beta_R P_{sat} k_{RE} g_{RE}}{N_o}, & g_{BS} \geq \frac{P_{sat}}{P\eta k_{BS}}, g_{BR} \geq \frac{P_{sat}}{P\eta k_{BR}} \end{cases}. \tag{16}$$

For ease of exposition, we denote g_{BS} by g_S, g_{BR} by g_R, k_{BS} by k_S and k_{BR} by k_R, $\alpha_S = \frac{P_{sat}}{P\eta k_{BS}}$, $\alpha_R = \frac{P_{sat}}{P\eta k_{BR}}$. Further, $\Omega_{SD} = \frac{\beta_S P k_S k_{SD}}{\beta_R N_o}$ denote average SNR of S-D link. Similarly, $\Omega_{SR} = \frac{\beta_S P k_S k_{SR}}{\beta_R N_o}$, $\Omega_{RD} = \frac{P k_R k_{RD}}{N_o}$, $\Omega_{SE} = \frac{\beta_S P k_S k_{SE}}{\beta_R N_o}$, $\Omega_{RE} = \frac{P k_S k_{RE}}{N_o}$ denote average SNR of S-R, R-D, S-E, and R-E links respectively. After phase II, the maximum mutual information of the combined signals are

$$I_{SRD} = \log_2(1+\Gamma_D), \quad \text{and} \quad I_{SRE} = \log_2(1+\Gamma_E), \tag{17}$$

with Γ_D and Γ_E given by (15) and (16) respectively.

III. Secrecy Outage Probability

In this section, we analyze the secrecy outage probability p_{os} of SDF and IDF signaling schemes (the DT scheme is used as a benchmark). In most literature on secrecy, the assumption of adaptive rate signaling is implicit, which implies that channel knowledge is assumed at the transmitter. The channel to E is however assumed to be unknown, which causes a secrecy outage. In many practical scenarios, such channel knowledge is not available at the transmitter, and fixed-rate signaling is used. Secrecy outage has been defined with and without incremental signaling for such scenarios in [30] assuming powered nodes.

Consider the case of IDF with fixed-rate signaling as used in this paper, there are three different secrecy outage events, depending on the success probability of the direct link and the probability of successful decoding at R: *i.)* When the signal from S to D is successfully decoded at D in phase I $(I_{SD} > R_t)$, a secrecy outage occurs when the information rate of the eavesdropping channel is more than the equivocation rate $(I_{SE} \geq R_e)$. *ii.)* When signal decoding at D fails in phase I $(I_{SD} < R_t)$, but R successfully decodes and cooperates with D in phase II, then secrecy outage occurs when either or both of the following events occur: a) main link is in outage $(I_{SRD} < R_t)$, and b) the capacity after combining at E is greater than the equivocation rate $(I_{SRE} \geq R_e)$. *iii.)* When both the S-D link and S-R link fail $((I_{SD} < R_t) \cap (I_{SR} < R_t))$ then secrecy outage occurs irrespective of decoding success at E. In summary, we can write the secrecy outage probability p_{os}^{IDF} with IDF as

$$p_{os}^{IDF} = \underbrace{\Pr\{(I_{SD} > R_t) \cap (I_{SE} \geq R_e)\}}_{p^{IDF}_{os,1}} + \underbrace{\Pr\{(I_{SD} < R_t) \cap (I_{SR} < R_t))\}}_{p^{IDF}_{os,3}} + \underbrace{\Pr\{(I_{SD} < R_t) \cap (I_{SR} \geq R_t) \cap ((I_{SRD} < R_t) \cup (I_{SRE} \geq R_e))\}}_{p^{IDF}_{os,2}}. \tag{18}$$

To write the secrecy outage expression for SDF (non-incremental relaying) we need to consider only the two following sub-cases: *i.)* when decoding at R fails $(I_{SR} < R_t)$, (so R cannot cooperate with D) secrecy outage event is the union of a) the S-D link failure event $(I_{SD} < R_t)$, and b) the event that capacity of the S-E link exceeds the equivocation rate $(I_{SE} \geq R_e)$. *ii.)* Decoding at R is successful, so R cooperates with D but decoding fails after combining at either one of D $(I_{SRD} < R_t)$ or E $(I_{SRE} \geq R_e)$. Clearly p_{os}^{SDF} is given by

$$p_{os}^{SDF} = \underbrace{\Pr\{(I_{SR} < R_t) \cap ((I_{SD} < R_t) \cup (I_{SE} \geq R_e))\}}_{p^{SDF}_{os,1}} + \underbrace{\Pr\{(I_{SR} \geq R_t) \cap ((I_{SRD} < R_t) \cup (I_{SRE} \geq R_e))\}}_{p^{SDF}_{os,2}}. \tag{19}$$

We present an approximate closed-form expression of secrecy outage for IDF and SDF signaling in the following lemmas.

Lemma 1. *An approximate expression for secrecy outage for multiple antenna with IDF signalling is*

$$p^{IDF}_{os.,mult.} \approx \frac{\gamma(M,\alpha_S)}{\Gamma(M)} + \frac{1}{\Gamma(M)} \sum_{m=0}^{N-1} \sum_{l=0}^{L-1} \frac{\gamma_{th}^m \gamma_{th,e}^l I_1}{m! l! \Omega_{SD}^m \Omega_{SE}^l} - I_2 + \frac{\Gamma(M,\alpha_S)\Gamma(N,\lambda_{SD})\Gamma(L,\lambda_{SE})}{\Gamma(L)\Gamma(N)\Gamma(M)} - \frac{1}{\Gamma(M)} \sum_{m=0}^{N-1} \frac{\gamma_{th}^m (I_3 - I_4)}{m! \Omega_{SD}^m} + \frac{(1-e^{-\lambda_{SR}})\gamma(N,\lambda_{SD})\Gamma(M,\alpha_S)}{\Gamma(N)\Gamma(M)} + p_{os,21}, \tag{20}$$

where $f(r) = \frac{\Gamma(2N-r)}{\Gamma^2(N)}\binom{N}{r}(-1)^{N-r-1}$, $\gamma_{th} = 2^{R_t} - 1$, $\gamma_{th,e} = 2^{R_e} - 1$, $\lambda_{SR} = \frac{\gamma_{th}\beta_R N_o}{\beta_S P_{sat} k_{SR}}$, $\lambda_{SD} = \frac{\gamma_{th}\beta_R N_o}{\beta_S P_{sat} k_{SD}}$, $\lambda_{RD} = \frac{\gamma_{th} N_o}{\beta_R P_{sat} k_{RD}}$, $\lambda_{SE} = \frac{\gamma_{th,e}\beta_R N_o}{\beta_S P_{sat} k_{SE}}$,

$\lambda_{RE}=\frac{\gamma_{th,e}N_o}{\beta_R P_{sat}k_{RE}}$, $I_1=\int_0^{\alpha_S} e^{-\frac{\gamma_{th}}{g_S\Omega_{SD}}-\frac{\gamma_{th,e}}{g_S\Omega_{SE}}-g_S} g_S^{M-m-l-1} dg_S$, $I_2=\int_0^{\alpha_S}\frac{e^{-g_S-\frac{\gamma_{th}}{g_S\Omega_{SR}}} g_S^{M-1}dg_S}{\Gamma(M)}$, $I_3=\int_0^{\alpha_S} e^{-\frac{\gamma_{th}}{g_S\Omega_{SD}}-g_S} g_S^{M-m-1}dg_S$, $I_4=\int_0^{\alpha_S} e^{-\frac{\gamma_{th}}{g_S\Omega_{SD}}-\frac{\gamma_{th}}{g_S\Omega_{SR}}-g_S} g_S^{M-m-1}dg_S$, *and* $p_{os,21}$ *is defined in* (21) *(on next page).*

Proof. See Appendix A. ■

Lemma 2. *An approximate expression for secrecy outage for multiple antenna with SDF signalling is*

$$p^{SDF}_{os.,mult.}=\frac{\gamma(M,\alpha_S)}{\Gamma(M)}-I_2-\sum_{m=0}^{N-1}\frac{\gamma_{th}^m I_1}{m!\Omega_{SD}^m\Gamma(M)}+\sum_{m=0}^{N-1}\frac{\gamma_{th}^m I_3}{m!\Omega_{SD}^m\Gamma(M)}$$
$$+\sum_{m=0}^{N-1}\sum_{l=0}^{L-1}\frac{\gamma_{th}^m\gamma_{th,e}^l(I_4-I_5)}{m!l!\Omega_{SD}^m\Omega_{SE}^l\Gamma(M)}+\frac{(1-e^{-\lambda_{SR}})\Gamma(M,\alpha_S)}{\Gamma(M)\Gamma(N)\Gamma(L)}$$
$$\times\Big[\gamma(N,\lambda_{SD})\Gamma(L)+\Gamma(N,\lambda_{SD})\Gamma(L,\lambda_{SE})\Big]+p_{os,21}+p_{os,22}, \quad (33)$$

where $f_e(r)\approx\frac{\Gamma(2L-r)\binom{L}{r}(-1)^{L-r-1}}{\Gamma^2(L)}$, $I_1=\int_0^{\alpha_S} e^{-\frac{\gamma_{th}}{g_S\Omega_{SD}}-g_S} g_S^{M-m-1}dg_S$,
$I_2=\int_0^{\alpha_S} e^{-\frac{\gamma_{th}}{g_S\Omega_{SR}}-g_S} g_S^{M-m-1}dg_S$,
$I_3=\int_0^{\alpha_S} e^{-\frac{\gamma_{th}}{g_S\Omega_{SD}}-\frac{\gamma_{th}}{g_S\Omega_{SR}}-g_S} g_S^{M-m-1}dg_S$,
$I_4=\int_0^{\alpha_S} e^{-\frac{\gamma_{th}}{g_S\Omega_{SD}}-\frac{\gamma_{th,e}}{g_S\Omega_{SE}}-g_S} g_S^{M-m-l-1}dg_S$,
$I_5=\int_0^{\alpha_S} e^{-\frac{\gamma_{th}}{g_S\Omega_{SD}}-\frac{\gamma_{th,e}}{g_S\Omega_{SE}}-\frac{\gamma_{th}}{g_S\Omega_{SR}}-g_S} g_S^{M-m-l-1}dg_S$.

Proof. We simplify $p^{SDF}_{os,1}$ in (19) by substituting I_{SR}, I_{SD} and I_{SE} from (9), (10), and (11) respectively, conditioning on EH channels g_S and g_R, further simplifying the resulting expression using the PDF of g_S and g_R, and using the series expansion of the lower incomplete gamma function [31, 8.352] (as in the derivation of $p^{IDF}_{os,1}$ in Appendix A). $p^{SDF}_{os,2}$ can be simplified using the identity $\Pr\{A\bigcup B\}=\Pr\{A\}+\Pr\{B\}-\Pr\{A\cap B\}$ for events A and B to get

$$p^{SDF}_{os,2}=\underbrace{\Pr\{(I_{SR}\geq R_t),(I_{SRD}<R_t)\}}_{p^{SDF}_{os,21}}+\underbrace{\Pr\{(I_{SR}\geq R_t),(I_{SRE}\geq R_e)\}}_{p^{SDF}_{os,22}}$$
$$-\underbrace{\Pr\{(I_{SR}\geq R_t),(I_{SRD}<R_t),I_{SRE}\geq R_e)\}}_{p^{SDF}_{os,23}}. \quad (34)$$

As with IDF, it can be shown $p^{SDF}_{os,2}\approx p^{SDF}_{os,21}+p^{SDF}_{os,22}$. The expression for $p^{SDF}_{os,21}$ is the same as $p^{IDF}_{os,21}$ (in Appendix A). Evaluation of $p^{SDF}_{os,22}$ follows on similar lines. ■

The expressions for secrecy outage in case of multiple antennas are complex to lend any analytical insights. Hence, we derive expressions for a single antenna system to deduce useful insights about the system behavior. We present an accurate expression of IDF scheme for a single antenna system in the following lemma.

Lemma 3. *An approximate expression for secrecy outage for IDF signaling with single antennas at B,D, and E (*$M=1,N=1,L=1$*) is*

$$p_{os}\approx p_{os,1}+p_{os,2}+p_{os,3}$$
$$p_{os,1}=\int_0^{\alpha_S} e^{-g_S-\frac{\gamma_{th}}{g_S\Omega_{SD}}-\frac{\gamma_{th,e}}{g_S\Omega_{SE}}}dg_S+e^{-\lambda_{SD}-\lambda_{SE}-\alpha_S}, \quad (35)$$
$$p_{os,2}\approx p_{os,21}, \quad (36)$$
$$p_{os,3}=\int_0^{\alpha_S} e^{-g_S}\big(1-e^{-\frac{\gamma_{th}}{g_S\Omega_{SR}}}\big)\big(1-e^{-\frac{\gamma_{th}}{g_S\Omega_{SD}}}\big)dg_S$$
$$+\big(1-e^{-\lambda_{SR}}\big)\big(1-e^{-\lambda_{SD}}\big)e^{-\alpha_S} \quad . \quad (37)$$

where $p_{os,21}$,is defined in (38).

Proof. See Appendix B. ■

Lemma 4. *An accurate approximate expression for* p^{IDF}_{os} *is given by* (39)

where $q_1=\frac{\gamma_{th}^2\Omega_{SR}}{\Omega_{RD}\Omega_{SD}(\Omega_{SR}-\Omega_{SD})}$, $q_2=\frac{\gamma_{th}^2}{\Omega_{RD}(\Omega_{SR}-\Omega_{SD})}$, $I=e^{-\alpha_S}(1-e^{-\alpha_R})-\frac{\gamma_{th}e^{-\alpha_S}Q_{RD}}{\Omega_{RD}}$, $Q_{SD}=e^{\frac{\gamma_{th}}{\Omega_{SD}}}E_1(\frac{\gamma_{th}}{\Omega_{SD}})-e^{\frac{\gamma_{th}}{\Omega_{SD}}}E_1(\alpha_S+\frac{\gamma_{th}}{\Omega_{SD}})$, $Q_{SR}=e^{\frac{\gamma_{th}}{\Omega_{SR}}}E_1(\frac{\gamma_{th}}{\Omega_{SR}})-e^{\frac{\gamma_{th}}{\Omega_{SR}}}E_1(\alpha_S+\frac{\gamma_{th}}{\Omega_{SR}})$, $Q_{RD}=e^{\frac{\gamma_{th}}{\Omega_{RD}}}E_1(\frac{\gamma_{th}}{\Omega_{RD}})-e^{\frac{\gamma_{th}}{\Omega_{RD}}}E_1(\alpha_R+\frac{\gamma_{th}}{\Omega_{RD}})$, and $d_{SR}=\nu d_{SD}$ (ν models the relative position of R with respect to S and D), $\Omega_{RD}=\tau\Omega_{SD}$ and $\tau=(1-\nu)^m$.

Proof. See Appendix C. ■

Remark 1. *A simplified expression of secrecy outage for the linear EH case (*$P_{sat}\to\infty$, $\alpha_S\to\infty$ *and* $\alpha_R\to\infty$*) is*

$$p^{IDF}_{os,approx.,HighSNR}\approx 1+\sqrt{\frac{4\gamma_{th}}{\Omega_{SD}}+\frac{4\gamma_{th,e}}{\Omega_{SE}}}K_1\Big(\sqrt{\frac{4\gamma_{th}}{\Omega_{SD}}+\frac{4\gamma_{th,e}}{\Omega_{SE}}}\Big)$$
$$-\sqrt{\frac{4\gamma_{th}}{\Omega_{SD}}}K_1\Big(\sqrt{\frac{4\gamma_{th}}{\Omega_{SD}}}\Big)-\sqrt{\frac{4\gamma_{th}}{\Omega_{SR}}}K_1\Big(\sqrt{\frac{4\gamma_{th}}{\Omega_{SR}}}\Big)+\sqrt{\frac{4\gamma_{th}}{\Omega}}K_1\Big(\sqrt{\frac{4\gamma_{th}}{\Omega}}\Big)$$
$$+q_1e^{\frac{\gamma_{th}}{\Omega_{SD}}+\frac{\gamma_{th}}{\Omega_{RD}}}E_1\Big(\frac{\gamma_{th}}{\Omega_{SD}}\Big)E_1\Big(\frac{\gamma_{th}}{\Omega_{RD}}\Big)-q_2e^{\frac{\gamma_{th}}{\Omega_{SR}}+\frac{\gamma_{th}}{\Omega_{RD}}}E_1\Big(\frac{\gamma_{th}}{\Omega_{SR}}\Big)E_1\Big(\frac{\gamma_{th}}{\Omega_{RD}}\Big). \quad (40)$$

Remark 2. *At high power,* $\Omega_{SD},\Omega_{SR}\gg\gamma_{th}$ *and* $\Omega_{SE}\gg\gamma_{th,e}$. *Using* $\lim_{x\to 0}K_1(x)\to\frac{\Gamma(1)}{2}\big(\frac{x}{2}\big)^{-1}$ *[32, 9.6.9], we have terms* $\sqrt{\frac{4\gamma_{th}}{\Omega_{SD}}+\frac{4\gamma_{th,e}}{\Omega_{SE}}}K_1\Big(\sqrt{\frac{4\gamma_{th}}{\Omega_{SD}}+\frac{4\gamma_{th,e}}{\Omega_{SE}}}\Big)\to 1$, $\sqrt{\frac{4\gamma_{th}}{\Omega_{SD}}}K_1\Big(\sqrt{\frac{4\gamma_{th}}{\Omega_{SD}}}\Big)\to 1$, $\sqrt{\frac{4\gamma_{th}}{\Omega_{SR}}}K_1\Big(\sqrt{\frac{4\gamma_{th}}{\Omega_{SR}}}\Big)\to 1$, $\sqrt{\frac{4\gamma_{th}}{\Omega}}K_1\Big(\sqrt{\frac{4\gamma_{th}}{\Omega}}\Big)\to 1$. *Also,* $q_1\to 0$, $q_2\to 0$, *as* $\Omega_{SD},\Omega_{SR},\Omega_{RD}\gg\gamma_{th}$ *and the terms* $e^{\frac{\gamma_{th}}{\Omega_{SD}}}E_1\Big(\frac{\gamma_{th}}{\Omega_{SD}}\Big)$, $e^{\frac{\gamma_{th}}{\Omega_{SR}}}E_1\Big(\frac{\gamma_{th}}{\Omega_{SR}}\Big)$ *and* $e^{\frac{\gamma_{th}}{\Omega_{RD}}}E_1\Big(\frac{\gamma_{th}}{\Omega_{RD}}\Big)$ *assume small finite values. So in* (39), $p^{IDF}_{os,approx.}\to 1$ *as expected. At low powers,* $\Omega_{SD},\Omega_{SR},\Omega_{RD}\ll\gamma_{th}$, *so the terms* $e^{\frac{\gamma_{th}}{\Omega_{SD}}}E_1\Big(\frac{\gamma_{th}}{\Omega_{SD}}\Big)\approx\frac{\Omega_{SD}}{\gamma_{th}}$, $e^{\frac{\gamma_{th}}{\Omega_{SR}}}E_1\Big(\frac{\gamma_{th}}{\Omega_{SR}}\Big)\approx\frac{\Omega_{SR}}{\gamma_{th}}$ *and* $e^{\frac{\gamma_{th}}{\Omega_{RD}}}E_1\Big(\frac{\gamma_{th}}{\Omega_{RD}}\Big)\approx\frac{\Omega_{RD}}{\gamma_{th}}$, *and the terms* $q_1e^{\frac{\gamma_{th}}{\Omega_{SR}}}E_1\Big(\frac{\gamma_{th}}{\Omega_{SR}}\Big)e^{\frac{\gamma_{th}}{\Omega_{RD}}}E_1\Big(\frac{\gamma_{th}}{\Omega_{RD}}\Big)$ *and* $q_2e^{\frac{\gamma_{th}}{\Omega_{SD}}}E_1\Big(\frac{\gamma_{th}}{\Omega_{SD}}\Big)e^{\frac{\gamma_{th}}{\Omega_{RD}}}E_1\Big(\frac{\gamma_{th}}{\Omega_{RD}}\Big)$ *cancel each other. Also,* $xK_1(x)\to 0$ *for large x so,* $p^{IDF}_{os,approx.}\to 1$ *once again.*

Remark 3. *When the legitimate nodes are more closely located than E,* $\Omega_{SD}\gg\Omega_{SE}$. *So,* $\Omega_{SD},\Omega_{SR}\gg\gamma_{th}$, $\sqrt{\frac{4\gamma_{th}}{\Omega_{SD}}+\frac{4\gamma_{th,e}}{\Omega_{SE}}}\approx\sqrt{\frac{4\gamma_{th,e}}{\Omega_{SE}}}$, $\sqrt{\frac{4\gamma_{th}}{\Omega_{SD}}}\to 0$, $\sqrt{\frac{4\gamma_{th}}{\Omega_{SR}}}\to 0$ *and* $\sqrt{\frac{4\gamma_{th}}{\Omega}}\to 0$. *Using* $\lim_{x\to 0}K_1(x)\to\frac{\Gamma(1)}{2}\big(\frac{x}{2}\big)^{-1}$ *[32, 9.6.9], terms* $\sqrt{\frac{4\gamma_{th}}{\Omega_{SD}}+\frac{4\gamma_{th,e}}{\Omega_{SE}}}K_1\Big(\sqrt{\frac{4\gamma_{th}}{\Omega_{SD}}+\frac{4\gamma_{th,e}}{\Omega_{SE}}}\Big)\to 1$, $\sqrt{\frac{4\gamma_{th}}{\Omega_{SD}}}K_1\Big(\sqrt{\frac{4\gamma_{th}}{\Omega_{SD}}}\Big)\to 1$, $\sqrt{\frac{4\gamma_{th}}{\Omega_{SR}}}K_1\Big(\sqrt{\frac{4\gamma_{th}}{\Omega_{SR}}}\Big)\to 1$, $\sqrt{\frac{4\gamma_{th}}{\Omega}}K_1\Big(\sqrt{\frac{4\gamma_{th}}{\Omega}}\Big)\to 1$. *Also,* $q_1\to 0$, $q_2\to 0$, *as* $\Omega_{SD},\Omega_{SR},\Omega_{RD}\gg\gamma_{th}$ *and terms* $e^{\frac{\gamma_{th}}{\Omega_{SD}}}E_1\Big(\frac{\gamma_{th}}{\Omega_{SD}}\Big)$, $e^{\frac{\gamma_{th}}{\Omega_{SR}}}E_1\Big(\frac{\gamma_{th}}{\Omega_{SR}}\Big)$ *and* $e^{\frac{\gamma_{th}}{\Omega_{RD}}}E_1\Big(\frac{\gamma_{th}}{\Omega_{RD}}\Big)$ *assume small finite values. So, in* (39), $p^{IDF}_{os,approx.}\approx\sqrt{\frac{4\gamma_{th,e}}{\Omega_{SE}}}K_1\Big(\sqrt{\frac{4\gamma_{th,e}}{\Omega_{SE}}}\Big)$. *Hence, secrecy outage is limited by the strength of the eavesdropping link*

$$p_{os,21} = p_{os,21|I} + p_{os,21|II} + p_{os,21|III} + p_{os,21|IV}, \tag{21}$$

$$p_{os,21|I} = \sum_{r=0}^{N-1} \frac{f(r)}{\Gamma^2(M)} \Big[\Omega_{SD}^{N-r-1} \Omega_{RD}^{N} I_{1d} - \sum_{k=0}^{2N-r-2} \Omega_{SD}^{N+2k} \Omega_{RD}^{N+k-r-1} I_{2d} \Big], I_{1d} = \int_0^{\alpha_S} \int_0^{\alpha_R} \frac{g_S^{M+N-r-2} g_R^{M+N-1} \gamma(r+1, \frac{\gamma_{th}}{g_R \Omega_{RD}}) e^{-g_S - \frac{\gamma_{th}}{g_S \Omega_{SR}} - g_R} dg_R dg_S}{(g_R \Omega_{RD} - g_S \Omega_{SD})^{2N-r-1}}, \tag{22}$$

$$I_{2d} = \int_0^{\alpha_S} \int_0^{\alpha_R} \frac{g_S^{M+N+2k-1} g_R^{M+N+k-r-2} \gamma(k+r+1, \frac{\gamma_{th}}{g_S \Omega_{SD}}) e^{-g_S - \frac{\gamma_{th}}{g_S \Omega_{SR}} - g_R} dg_R dg_S}{k!(g_R \Omega_{RD} - g_S \Omega_{SD})^{2N+k-r-1}}, \tag{23}$$

$$p_{os,21|II} = \frac{\Gamma(M, \alpha_S) e^{-\lambda_{SR}}}{\Gamma^2(M)\Gamma(N)} \left[\gamma(M, \alpha_R)\gamma(N, \lambda_{SD}) - \sum_{m=0}^{N-1} \sum_{l=0}^{m} \binom{m}{l} \frac{(-1)^l \gamma_{th}^m \beta_R^m}{m! \Omega_{RD}^m \lambda_{SD}^l} \gamma(l+N, \lambda_{SD}) I_{P21}(l,m) \right], \tag{24}$$

$$p_{os,21|III} = \frac{\Gamma(M, \alpha_R)}{\Gamma^2(M)\Gamma(N)} \left[\gamma(N, \lambda_{RD}) I_{P31} - \sum_{m=0}^{N-1} \sum_{l=0}^{m} \binom{m}{l} \frac{(-1)^l \gamma_{th}^m}{m! \Omega_{SD}^m \lambda_{RD}^l} \gamma(l+N, \lambda_{RD}) I_{P32}(l,m) \right], \tag{25}$$

$$p_{os,21|IV} = \frac{e^{-\lambda_{SR}} \Gamma(M, \alpha_S) \Gamma(M, \alpha_R)}{\Gamma(N)\Gamma^2(M)} \left[\gamma(N, \lambda_{RD}) - e^{-\lambda_{RD}} \sum_{m=0}^{N-1} \sum_{l=0}^{m} \frac{(-1)^l \lambda_{SD}^{m-l} k_{RD}^l \gamma\Big(N+l, \frac{\lambda_{SD}(\delta k_{SD} - k_{RD})}{k_{RD}}\Big)}{(\delta k_{SD})^{l-1} (\delta k_{SD} - k_{RD}) m!} \right]. \tag{26}$$

$$I_{P21}(l,m) = \int_0^{\alpha_R} \frac{e^{-g_R - \frac{\gamma_{th}\beta_R}{g_R \Omega_{RD}}} g_R^{M-m-1} dg_R}{\Gamma(M) \left(1 - \frac{\gamma_{th}\beta_R}{g_R \Omega_{RD} \lambda_{SD}}\right)^{l+N}}, \qquad I_{P31} = \int_0^{\alpha_S} \frac{e^{-\frac{\gamma_{th}}{g_S \Omega_{SR}} - g_S} g_S^{M-1} dg_S}{\Gamma(M)}, \qquad I_{P32}(l,m) = \int_0^{\alpha_S} \frac{e^{-\frac{\gamma_{th}}{g_S \Omega_{SD}} - \frac{\gamma_{th}}{g_S \Omega_{SR}} - g_S} g_S^{M-m-1} dg_S}{\Gamma(M) \left(1 - \frac{\gamma_{th}}{g_S \Omega_{SD} \lambda_{RD}}\right)^{l+N}}. \tag{27}$$

$$p_{os,22|I} = \sum_{r=0}^{L-1} \frac{f_e(r)}{\Gamma^2(M)} \Big[\Omega_{SE}^{L-r-1} \Omega_{RE}^{L} I_{1e} - \sum_{k=0}^{2L-r-2} \Omega_{SE}^{L} \Omega_{RE}^{L-r-k-1} I_{2e} \Big], I_{1e} = \int_0^{\alpha_S} \int_0^{\alpha_R} \frac{g_S^{M+L-r-2} g_R^{M+L-1} \gamma(r+1, \frac{\gamma_{th,e}}{g_R \Omega_{RE}}) e^{-\frac{\gamma_{th}}{g_S \Omega_{SR}} - g_S - g_R} dg_R dg_S}{(g_R \Omega_{RE} - g_S \Omega_{SE})^{2L-r-1}}, \tag{28}$$

$$I_{2e} = \int_0^{\alpha_S} \int_0^{\alpha_R} \frac{g_S^{M+L-1} g_R^{M+L-r-k-2} \gamma(k+r+1, \frac{\gamma_{th}}{g_S \Omega_{SE}}) e^{-\frac{\gamma_{th}}{g_S \Omega_{SR}} - g_S - g_R} dg_R dg_S}{k!(g_R \Omega_{RE} - g_S \Omega_{SE})^{2L-r-k-1}}, \tag{29}$$

$$p_{os,22|II} = \frac{\Gamma(M, \alpha_S) e^{-\lambda_{SR}}}{\Gamma^2(M)\Gamma(L)} \Big[\gamma(M, \alpha_R)\Gamma(L, \lambda_{SE}) + \sum_{m=0}^{L-1} \sum_{l=0}^{m} \binom{m}{l} \frac{(-1)^l \gamma_{th,e}^m \beta_R^m \gamma(l+L, \lambda_{SE}) I_{Q21}(l,m)}{m! \Omega_{RE}^m \lambda_{SE}^l} \Big],$$

$$p_{os,22|III} = \frac{\Gamma(M, \alpha_S)}{\Gamma^2(M)\Gamma(L)} \Big[\Gamma(L, \lambda_{RE}) I_{P31} + \sum_{m=0}^{L-1} \sum_{l=0}^{m} \binom{m}{l} \frac{(-1)^l \gamma_{th,e}^m \gamma(l+L, \lambda_{RE}) I_{Q23}(l,m)}{m! \Omega_{SE}^m \lambda_{RE}^l} \Big], \tag{30}$$

$$p_{os,22|IV} = \frac{e^{-\lambda_{SR}} \Gamma(M, \alpha_S) \Gamma(M, \alpha_R)}{\Gamma^2(M)\Gamma(L)} \Big[\Gamma(L, \lambda_{RE}) + e^{-\lambda_{SE}} \sum_{m=0}^{L-1} \sum_{l=0}^{m} \frac{\lambda_{SE}^{m-l} (-1)^l k_{RE}^l \gamma\Big(L+l-1, \frac{\lambda_{SE}(\delta k_{SE} - k_{RE})}{k_{RE}}\Big)}{(\delta k_{SE})^{l-1} (\delta k_{SE} - k_{RE}) m!} \Big]. \tag{31}$$

$$I_{Q21}(l,m) = \int_0^{\alpha_R} \frac{e^{-g_R - \frac{\gamma_{th,e}\beta_R}{g_R \Omega_{RE}}} g_R^{M-m-1}}{\Gamma(M) \left(1 - \frac{\gamma_{th}\beta_R}{g_R \Omega_{RE} \lambda_{SE}}\right)^{l+L}} dg_R, I_{Q23}(l,m) = \int_0^{\alpha_S} \frac{e^{-g_S - \frac{\gamma_{th,e}}{g_S \Omega_{SE}}} e^{-\frac{\gamma_{th}}{g_S \Omega_{SR}}} g_S^{M-1}}{\Gamma(M) \left(1 - \frac{\gamma_{th,e}}{g_S \Omega_{SE} \lambda_{RE}}\right)^{l+L}} dg_S. \tag{32}$$

and there exists a performance floor. To achieve a lower secrecy outage, the strength of the eavesdropping link has to be reduced (for example by jamming).

Remark 4. *When E is more closely located to S than D, $\Omega_{SE} \gg \Omega_{SD}$ so that $\sqrt{\frac{4\gamma_{th}}{\Omega_{SD}} + \frac{4\gamma_{th,e}}{\Omega_{SE}}} \approx \sqrt{\frac{4\gamma_{th}}{\Omega_{SD}}}$. At sufficiently high powers ($\Omega_{SD}, \Omega_{SR} \gg \gamma_{th}$), $\sqrt{\frac{\gamma_{th}}{\Omega_{SR}}} \to 0$, and $\sqrt{\frac{\gamma_{th}}{\Omega}} \to 0$. Therefore, $\sqrt{\frac{4\gamma_{th}}{\Omega_{SR}}} K_1\left(\sqrt{\frac{4\gamma_{th}}{\Omega_{SR}}}\right) \to 1$ and $\sqrt{\frac{4\gamma_{th}}{\Omega}} K_1\left(\sqrt{\frac{4\gamma_{th}}{\Omega}}\right) \to 1$. Also, $q_1 \to 0$, $q_2 \to 0$ and terms $e^{\frac{\gamma_{th}}{\Omega_{SD}}} E_1\left(\frac{\gamma_{th}}{\Omega_{SD}}\right)$, $e^{\frac{\gamma_{th}}{\Omega_{SR}}} E_1\left(\frac{\gamma_{th}}{\Omega_{SR}}\right)$ and $e^{\frac{\gamma_{th}}{\Omega_{RD}}} E_1\left(\frac{\gamma_{th}}{\Omega_{RD}}\right)$ assume small finite values. Hence $p_{os,approx}^{IDF} \to 1$ (secrecy outage is a certain event).*

It is evident from Remark 1 that with small transmit powers, the direct link is often in outage, and R re-transmits when it can successfully decode. The re-transmissions from R are observed by E, which weakens secrecy, so p_{os} is high. When the transmit power is high, the direct link is successful with high probability, and the direct link to E is also sufficiently strong, secrecy outage occurs, and p_{os} is large once again. A critical transmit power P of PB certainly exists at which p_{os} is the smallest. We pose this optimization problem as

$$P^* = \arg\min_P \quad p_{os}. \tag{41}$$

In the following lemma, we establish the convexity of p_{os} with respect to power P. We provide proof of convexity for IDF signaling (proof for SDF signaling follows along similar lines).

Lemma 5. *The secrecy outage probability p_{os}^{IDF} is a convex function of transmit power P.*

Proof. Convexity of p_{os}^{IDF} can be established using high SNR expression in (40) by showing second derivative is positive. Detailed proof is given in Appendix D. ■

$$p_{os,21}=\underbrace{\int_0^{\alpha_S}\int_0^{\alpha_R} e^{-g_S-g_R-\frac{\gamma_{th}}{g_S\Omega_{SR}}}\Big[1-\frac{(g_R\Omega_{RD}e^{-\frac{\gamma_{th}}{g_R\Omega_{RD}}}-g_S\Omega_{SD}e^{-\frac{\gamma_{th}}{g_S\Omega_{SD}}})}{(g_R\Omega_{RD}-g_S\Omega_{SD})}\Big]dg_R dg_S}_{p_{os,21|I}}+\underbrace{e^{-\lambda_{SR}}\Big[1-\frac{(\beta_R k_{RD}e^{-\lambda_{RD}}-\beta_S k_{SD}e^{-\lambda_{SD}})}{(\beta_R k_{RD}-\beta_S k_{SD})}\Big]e^{-\alpha_S}e^{-\alpha_R}}_{p_{os,21|IV}}$$

$$+\underbrace{\int_0^{\alpha_R} e^{-\alpha_S-g_R-\lambda_{SR}}\Big[1-e^{-\lambda_{SD}}-\frac{\big[e^{-\frac{\gamma_{th}}{g_R\Omega_{RD}}}-e^{-\lambda_{SD}}\big]}{\big(1-\frac{c\beta_R}{g_R\Omega_{RD}\lambda_{SD}}\big)}\Big]dg_R}_{p_{os,21|II}}+\underbrace{\int_0^{\alpha_S} e^{-g_S-\alpha_R-\frac{\gamma_{th}}{g_S\Omega_{SR}}}\Big[1-e^{-\lambda_{RD}}-\frac{\big[e^{-\frac{\gamma_{th}}{g_S\Omega_{SD}}}-e^{-\lambda_{RD}}\big]}{\big(1-\frac{\gamma_{th}}{g_S\Omega_{SD}\lambda_{RD}}\big)}\Big]dg_S}_{p_{os,21|III}}, \quad (38)$$

$$p^{IDF}_{os,approx.}\approx 1+\sqrt{\frac{4\gamma_{th}}{\Omega_{SD}}+\frac{4\gamma_{th,e}}{\Omega_{SE}}}K_1\Big(\sqrt{\frac{4\gamma_{th}}{\Omega_{SD}}+\frac{4\gamma_{th,e}}{\Omega_{SE}}}\Big)-\sqrt{\frac{4\gamma_{th}}{\Omega_{SD}}}K_1\Big(\sqrt{\frac{4\gamma_{th}}{\Omega_{SD}}}\Big)-\sqrt{\frac{4\gamma_{th}}{\Omega_{SR}}}K_1\Big(\sqrt{\frac{4\gamma_{th}}{\Omega_{SR}}}\Big)+\sqrt{\frac{4\gamma_{th}}{\Omega}}K_1\Big(\sqrt{\frac{4\gamma_{th}}{\Omega}}\Big)$$
$$+p_{os,21|I}+p_{os,21|II}+p_{os,21|III}+p_{os,21|IV}$$

$$p_{os,21|I}\approx q_1 Q_{SD}Q_{RD}-q_2 Q_{SR}Q_{RD}, \quad p_{os,21|II}\approx(1-e^{-\lambda_{SD}})e^{-\lambda_{SR}}(1-e^{-\alpha_R})e^{-\alpha_S}-\frac{\lambda_{SD}e^{-\lambda_{SR}}I}{(1+\lambda_{SD})},$$

$$p_{os,21|III}\approx\big(1-e^{-\lambda_{RD}}\big)\big(1-e^{-\alpha_S}\big)e^{-\alpha_R}-\big(1-e^{-\lambda_{RD}}\big)\frac{\gamma_{th}e^{-\alpha_R}Q_{SR}}{\Omega_{SR}}-\frac{\lambda_{RD}(1-e^{-\alpha_S})e^{-\alpha_R}}{(1+\lambda_{RD})}-\frac{c\Omega_{SR}\lambda_{RD}e^{-\alpha_R}Q_{SD}}{\Omega_{SD}(\Omega_{SD}-\Omega_{SR})(1+\lambda_{RD})}$$

$$+\frac{c\Omega_{SD}\lambda_{RD}e^{-\alpha_R}Q_{SR}}{\Omega_{SR}(\Omega_{SD}-\Omega_{SR})(1+\lambda_{RD})}, \quad p_{os,21|IV}\approx\Big[1-\frac{(\beta_R k_{RD}e^{-\lambda_{RD}}-\beta_S k_{SD}e^{-\lambda_{SD}})}{(\beta_R k_{RD}-\beta_S k_{SD})}\Big]e^{-\lambda_{SR}}e^{-\alpha_S}e^{-\alpha_R}, \quad (39)$$

Remark 5. *Unfortunately, the optimal value P^* cannot be expressed in closed form. However, P^* can readily be evaluated numerically.*

Remark 6. *It can be shown analytically that $p^{SDF}_{os,approx.}\geq p^{IDF}_{os,approx.}$, which implies that SDF signaling is less secure than IDF signaling. Note that re-transmissions from R aid both D and E. For lower transmit powers, the performance of SDF is similar to that of IDF since the direct link is often in an outage in such scenarios, and IDF signaling essentially amounts to SDF signaling. As the transmit power increases marginally, frequent relay re-transmissions degrade the secrecy performance with SDF. However, since frequent relay transmissions are avoided with the IDF scheme, its secrecy performance is superior in this power range. We show later that even reducing transmit power at R in a power backoff scheme helps in improving secrecy performance with IDF signaling.*

IV. Secrecy improvement using power back-off

In this section, we establish how power back-off can be used at S and R to improve the secrecy performance of the considered wireless-powered cooperative network (although it clearly degrades outage). The effectiveness of power back-off is later demonstrated by extensive simulations.

A. Power back-off at the Relay

As noted earlier, IDF signaling offers better secrecy than SDF signaling. We show here that when E is closer to R than S, there exists an optimal value of this back-off parameter β^*_R that ensures best secrecy. We pose this optimization problem as

$$\beta^*_R=\arg\min_{0<\beta_R<1} \quad p_{os}. \quad (42)$$

We bring out the feature of this optimization problem in the following lemma.

Lemma 6. *The secrecy outage probability $p^{IDF}_{os,approx}$ ($p^{SDF}_{os,approx}$) is a convex function of the power back-off parameter β_R when E is closer to R than the S, and there exists an optimal value of the power back-off parameter $\beta^{*,IDF}_R$ and ($\beta^{*,SDF}_R$) that minimizes the secrecy outage.*

Proof. Detailed proof is given in Appendix E. ■

Remark 7. *Although the optimal power back-off parameters $\beta^{*,IDF}_R$ and $\beta^{*,IDF}_R$ cannot be expressed in closed form, they can be readily evaluated by a 1-D offline search. The amount of improvement in secrecy is more with SDF than IDF due to frequent re-transmissions by R in the latter case.*

B. Power back-off at the Source

In this subsection, we show that power back-off at S can improve secrecy under certain conditions. Assuming P is large, the direct link is successful with a high probability, and leakage of information from R to E is practically non-existent. In these cases, S can operate at reduced power by applying power back-off β_S while maintaining the required outage constraint $p_{out}<\varepsilon$. Hence, when the main channel is stronger than the eavesdropping channel (widely studied in literature), any reduction in power will marginally reduce the SNR of the main channel while significantly reducing the SNR of the eavesdropping channel. So, gain in secrecy is attained by power back-off. This occurs till a certain power P^* at the beacon. Any further decrement in the power at S will make the S-D link weak, and the R will start cooperating with D (thereby leaking information to E and thus reducing secrecy). There exists an optimal value of this back-off parameter which gives minimum secrecy outage performance. We pose this optimization problem as

$$\beta^*_S=\arg\min_{0<\beta_S<1} \quad p_{os}. \quad (43)$$

We present the following lemma based on this observation.

Lemma 7. *The secrecy outage probability $p^{IDF}_{os,approx.}$ is a convex function of the power back-off parameter β_S, and* *there exists an optimal value $\beta_S^{*,IDF}$ of the power back-off parameter that minimizes the secrecy outage.*

Proof. Detailed proof is given in Appendix E. ■

Remark 8. *Unfortunately, the optimal power back-off parameter $\beta_S^{*,IDF}$ cannot be expressed in closed form. However, $\beta_S^{*,IDF}$ can readily be evaluated numerically. Similar to IDF signaling, secrecy outage with SDF signaling can also be further improved by employing power back-off at the source. Proof of convexity of $p_{os,approx.}^{SDF}$ with respect to β_S follows on similar lines.*

In scenarios where E is not distant from R and $P > P^*$, joint power back-off both at S and R improves secrecy performance. There exists optimal values of back-off parameters (β_S, β_R). We pose this optimization problem as

$$(\beta_S^*, \beta_R^*) = \arg \min_{0<\beta_S, \beta_R<1} p_{os}. \tag{44}$$

Lemma 8. *The secrecy outage probability $p_{os,approx.}^{IDF}$ is jointly convex with power back-off parameters (β_S, β_R), and there exist optimal values of $(\beta_S^{*,IDF}, \beta_R^{*,IDF})$ at source and relay that minimize the secrecy outage.*

Proof. Detailed proof is given in Appendix F. ■

The individual power back-off studied earlier (at only S or R) is a special case of joint power back-off. When E is closer to R and the network is operating at $P = P^*$, joint back-off reduces to individual back-off at R. In contrast, when E is far from R and the network is operating at $P > P^*$, joint back-off reduces to individual back-off at S. In table II, we indicate the back-off conditions for different operating conditions of the network. In this sub-section, we studied the importance of power back-off to improve secrecy outage while degrading the outage performance. We further study this interdependence of secrecy and reliability as a security-reliability trade-off (SRT) in the next subsection.

TABLE II: Power back-off conditions at S and R

Network Condition	**Back-off at R**	**Back-off at S**
$P \geq P^*$, E is close to R	Yes	Yes
$P < P^*$, E is close to R	Yes	No
$P \geq P^*$, E is not close to R	Yes	Yes
$P < P^*$, E is not close to R	No	No
$P \geq P^*$, E is far from R	No	Yes
$P < P^*$, E is far from R	No	No

V. Security-Reliability Trade-off

In recent years, security-reliability trade-off (SRT) has been analyzed [33]–[35] to study the interplay of security and reliability in communication networks. In this section, we analyze the SRT of a self-sustainable cooperative network for the first time. It is evident from the discussions in the previous section on power back-off that as we increase the power P of the power beacon, both S and R harvest an increased amount of energy. This ensures improvement in reliability performance. However, this also leads to an increased risk of eavesdropping, and thereby poor secrecy performance. On the other hand, decreasing P reduces the reliability of the network, leading to reduced leakage of information to E, and hence improved secrecy. To establish SRT, we derive an expression for outage probability (p_{OP}) and intercept probability (p_{IP}) for the main and eavesdropping link, respectively. In case of IDF signaling, an outage occurs when the S-D link fails, and the S-R-D link after combining the direct and relayed signals has inadequate SNR [36]. Further, information rate at E exceeds the information rate R_t interception by E occurs. Hence p_{OP} and p_{IP} will be

$$p_{OP}^{IDF} = \Pr\{I_{SD} < R_t\} \Pr\{\min(I_{SR}, I_{SRD}) \leq R_t | I_{SD} < R_t\}, \tag{45}$$

$$p_{IP}^{IDF} = \Pr\{I_{SD} \geq R_t, I_{SE} > R_t\} + \Pr\{I_{SD} < R_t, I_{SRE} > R_t\}. \tag{46}$$

We present an expression for outage probability with the IDF relaying scheme with multiple antennas for linear EH ($\alpha \to \infty$, $\beta \to \infty$) in the following lemma.

Lemma 9. *The outage probability with the IDF relaying scheme can be expressed as*

$$\begin{aligned} p_{OP}^{IDF} =& 1 - \sum_{m=1}^{N-1} \frac{2\gamma_{th}^{m+M/2}}{m!\Omega_{SD}^{m+M/2}} K_M\left(\sqrt{\frac{4\gamma_{th}}{\Omega_{SD}}}\right) - \sum_{m=0}^{N-1} \sum_{r=0}^{m} \binom{m}{r} \\ &\times \int_0^\infty\int_0^\infty e^{-\frac{\gamma_{th}}{g_S\Omega_{SR}} - \frac{\gamma_{th}}{g_R\Omega_{RD}}} \frac{\gamma_{th}^{m-r}\Omega_{SD}^r \Omega_{RD}^{N-m+r} g_S^{M+r-1} g_R^{M+N+r-m-1}}{m!\Gamma(N)\Gamma^2(M)(g_R\Omega_{RD} - g_S\Omega_{SD})} \\ &\times e^{-g_S - g_R} \gamma\left(N + r - 1, \frac{\gamma_{th}(g_R\Omega_{RD} - g_S\Omega_{SD})}{g_R\Omega_{RD} g_S\Omega_{SD}}\right) dg_R dg_S. \end{aligned} \tag{47}$$

Proof. Detailed proof is given in Appendix G. ■

We now present an expression for intercept probability for the IDF scheme in the following lemma.

Lemma 10. *The exact expression for the intercept probability with the IDF relaying scheme is*

$$\begin{aligned} p_{IP}^{IDF} =& \frac{1}{\Gamma(M)} \sum_{m=0}^{N-1} \sum_{l=0}^{L-1} \frac{2\gamma_{th}^{m+l}}{m!l!\Omega_{SD}^m \Omega_{SE}^l} \left(\frac{\gamma_{th}}{\Omega_{SD}} + \frac{\gamma_{th}}{\Omega_{SE}}\right)^{(M-m-l)/2} \\ &\times K_{M-m-l}\left(2\sqrt{\frac{\gamma_{th}}{\Omega_{SD}} + \frac{\gamma_{th}}{\Omega_{SE}}}\right) + \frac{\Omega_{SE}^{L-r-1}\Omega_{RE}^L}{\Gamma(N)\Gamma^2(M)} \sum_{r=0}^{L-1} f_e(r) \int_0^\infty\int_0^\infty e^{-g_S - g_R} \\ &\times \frac{g_S^{M+L-r-2} g_R^{M+L-1} \Gamma\left(r+1, \frac{\gamma_{th}}{g_R\Omega_{RE}}\right) \gamma\left(N, \frac{\gamma_{th}}{g_S\Omega_{SD}}\right)}{(g_R\Omega_{RE} - g_S\Omega_{SE})^{2L-r-1}} dg_S dg_R \\ &- \sum_{r=0}^{L-1} \sum_{k=0}^{2L-r-2} \frac{f_e(r)\Omega_{SE}^L \Omega_{RE}^{L-r-k-1}}{k!} \int_0^\infty\int_0^\infty \frac{g_S^{M+L-1} g_R^{M+L-r-k-2}}{(g_R\Omega_{RE} - g_S\Omega_{SE})^{2L-r-k-1}} \\ &\times e^{-g_S - g_R} \Gamma(k + r + 1, \gamma_{th}/(g_S\Omega_{SE})) \gamma(N, \gamma_{th}/(g_S\Omega_{SD})) dg_S dg_R. \end{aligned} \tag{48}$$

Proof. Detailed proof is given in Appendix H. ■

VI. Simulation and Numerical Results

In this section, we numerically evaluate expressions for secrecy outage with DT, SDF and IDF schemes. We study the effect of transmit power as well as power back off (both at S and R) on secrecy. Also, we demonstrate the existence of SRT in a PB-based cooperative network. We validate the analytical results in the paper through Monte Carlo simulations. We consider distances $d_{SD} = 10$ m, $d_{SE} = 10$ m, $d_{RE} = 10$ m, $d_{BS} = 5$ m and $d_{BR} = 5$ m. The path-loss exponent $m = 4$, and the reference distance for antenna far-field is $d_0 = 1$ m. The carrier frequency $f_c = 2.4$ GHz, and the transmission bandwidth $B_w = 10$ MHz. Further, $N_o = -93$ dBm. We consider $R_t = 3$ bpcu (bits per channel use) and equivocation rate $R_e = 2$ bpcu so that so secrecy transmit rate is $R_s = R_t - R_e = 1$ bpcu. We assume that the legitimate nodes are along a line, with the relay being equidistant from S and D ($d_{SR} = 0.5 d_{SD}$).

In Fig.2 and Fig.3, we plot the exact and approximate expressions for p_{os} with respect to Ω_{SD} ($\Omega_{SD} = \frac{\delta P k_S k_{SD}}{N_o}$) for DT, SDF, and IDF schemes and compare with simulation results. We assume two scenarios a) E is equidistant from S and R ($\Omega_{SE} = \Omega_{RE}$) and b) E is closer to R than S ($\Omega_{RE} = 4\Omega_{SE}$). In both scenarios, we observe perfect agreement between simulation and analytical results. Moreover, in Fig. 2 and 3 the secrecy outage exhibits a floor since p_{os} is limited by the large eavesdropper's link SNR. As we gradually increase Ω_{SD}, the strength of the main link increases. Hence, secrecy performance improves for both SDF and IDF schemes. Further increase in Ω_{SD} results in better performance of IDF over SDF scheme. This happens due to reduced leakage of information symbols from R during re-transmissions when the S-D link fails. In Fig. 3, E is close to R. This enhanced R-E link leaks more information to E with SDF than IDF. Clearly, the IDF scheme provides better physical layer security.

In Fig. 4, we study effect of link quality of the eavesdropping link Ω_{SE} on secrecy outage when d_{RE} is fixed ($\Omega_{RE} = 0dB$). As we increase Ω_{SE}, p_{os} decreases since E is brought closer to S (S-E link quality increases, hence secrecy degrades). Moreover, IDF performs better than SDF for low Ω_{SE}. At high Ω_{SE} both schemes fail to provide secrecy.

In Fig. 5, we plot p_{os} with respect to P. In the low transmit power regime, the performance of SDF and IDF is similar since the direct link fails to support the required target rate in many instances, and the relay re-transmits the symbol to the destination. As we increase the beacon's transmit power, re-transmissions from R is less frequent with IDF than with SDF, thus decreasing the chance of leaking information symbols to E. Hence IDF performs better than SDF in terms of secrecy. Further increase in transmit power increases the probability of correct detection in both direct and eavesdropping links, leading to an increase in p_{os}. In the high P regime, the performance of IDF is similar to that of DT, while the performance of SDF is even poorer than DT due to leakage of information from re-transmissions from R. Clearly there exists an optimal power of PB which minimizes the p_{os}.

In Fig. 6 and 7, we plot p_{os} with respect to the power back-off parameter β_R at R for IDF and SDF respectively. When E is close to R, re-transmissions from R to D leads to information leakage to E. This loss in secrecy can be minimized by using less transmit power ($\beta_R < 1$) at R. There exists an optimal power back-off parameter β_R^* which minimizes secrecy outage for a given R-E distance. This is consistent with *lemma* 6. As E is moved closer to R, the parameter β_R^* becomes smaller, signifying that lower transmit power at R ensures the best secrecy outage performance. This also leads to energy savings at R, and the residual energy can be used at R for its routine circuit operation. Power back-off parameter evaluated numerically matches closely with the simulation result. Also, improvement with power back-off is higher with SDF than IDF due to re-transmissions from R in the former leading to leakage of information to E. This leakage is reduced by back-off at R to a greater extent with SDF than with IDF signaling.

In Fig. 8 and 9, we plot p_{os} (with IDF and SDF respectively) with respect to the power back-off parameter β_S at S for different S-E distances. For a given outage constraint of the network, we note later that this corresponds to a point of operation on the SRT curve plotted in Fig. 10. The source can operate with larger power back-off in order to reduce secrecy outage while increasing p_{out}, thus moving the operating point on the SRT curve towards right (increase in p_{out}). This power back-off leads to energy savings at S and improvement in p_{os}. Also, there exists an optimal power back-off parameter β_S^* which minimizes secrecy outage by reducing the transmit power of S while yielding sub-optimal outage performance. The approximate power back-off parameter evaluated numerically matches closely with the exact power back-off parameter.

In Fig. 10, we plot p_{ip} versus p_{out} for different MER values $\lambda_{me} = 25$ dB and $\lambda_{me} = 35$ dB. The plot clearly signifies the existence of a trade-off between security and reliability in self-sustaining cooperative nodes. The SRT curve of DT is above that of IDF, clearly suggesting improvement in the trade-off. This shows that the use of incremental signaling relaying improves both outage and secrecy performance. However, both of these quantities are interlinked, and improving intercept probability leads to poorer outage performance, and vice-versa. Also, as we increase the strength of the main to eavesdropper channel the improvement in SRT offered by IDF over the DT schemes also increases, suggesting the benefits of using an incremental signaling. Further, when the outage probability constraint is small, we are operating at the top-left corner of the SRT curve. S applies power back-off in order to attain a larger outage at the expense of lower intercept probability. At high SNR, the SRT performance of the IDF scheme is superior to SDF, while at low SNR SDF performs better than IDF in terms of SRT.

VII. Conclusion

In this paper, we analyzed the secrecy performance of a cooperative network with self-sustaining energy harvesting nodes assuming fixed-rate signalling. The nodes were assumed to harvest energy from a power beacon. Optimal combining was used at both the destination and the eavesdropper. We analyzed the secrecy outage performance of selective decode and forward (SDF) and incremental decode and forward (IDF) relaying schemes. It was shown that the latter ensures much better secrecy performance. The security reliability trade-off of such networks was analyzed to derive insights. It was established that the secrecy outage is a convex function of the power beacon power. An optimal value of the power beacon power exists that minimizes

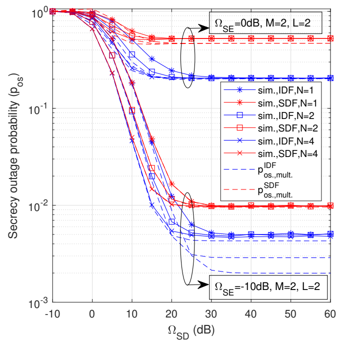


Fig. 2: p_{os} of SDF, IDF schemes versus Ω_{SD} with $\Omega_{RE} = \Omega_{SE}$.

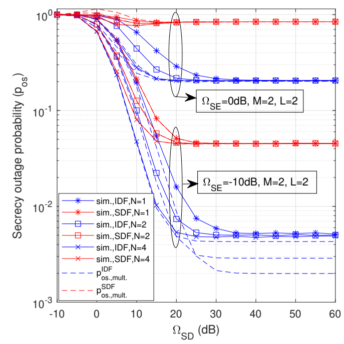


Fig. 3: p_{os} of SDF, IDF schemes versus Ω_{SD} with $\Omega_{RE} = 4\Omega_{SE}$.

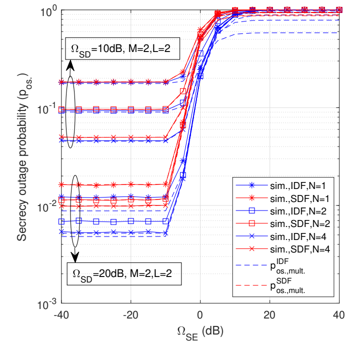


Fig. 4: p_{os} of SDF, IDF schemes versus Ω_{SE} with $\Omega_{RE} = \Omega_{SE}$.

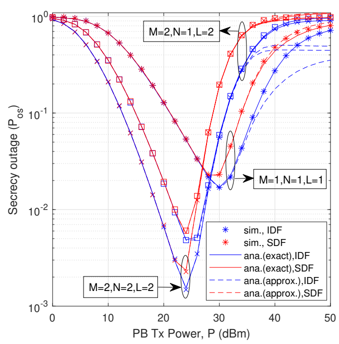


Fig. 5: p_{os} vs. P for SDF, IDF schemes, $\lambda_{me} = 30dB$.

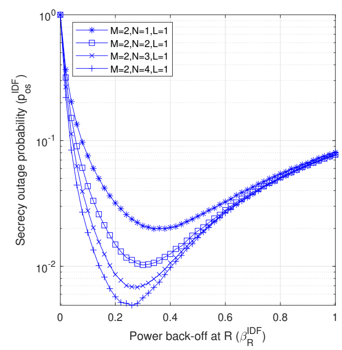


Fig. 6: p_{os}^{IDF} vs. β_R^{IDF}, $P = 25dBm$, $d_{RE} = 2m$, $\lambda_{me} = 30dB$.

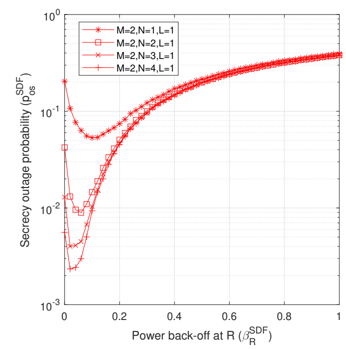


Fig. 7: p_{os}^{SDF} vs. β_R^{SDF}, $P = 25dBm$, $d_{RE} = 2m$, $\lambda_{me} = 30dB$.

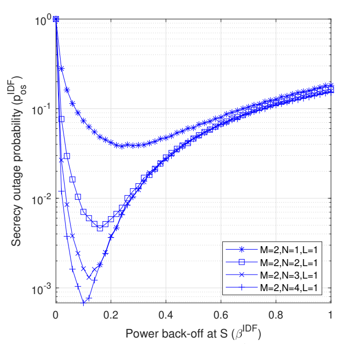


Fig. 8: p_{os}^{IDF} vs. β_s, $P = 25dBm$, $d_{SE} = 5m$, $\lambda_{me} = 30dB$.

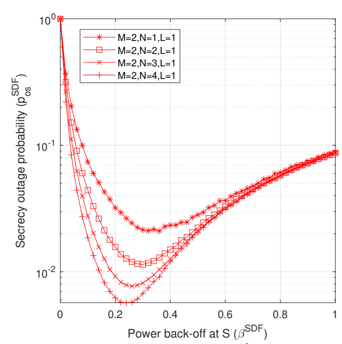


Fig. 9: p_{os}^{SDF} vs. β_s, $P = 25dBm$, $d_{SE} = 5m$, $\lambda_{me} = 30dB$.

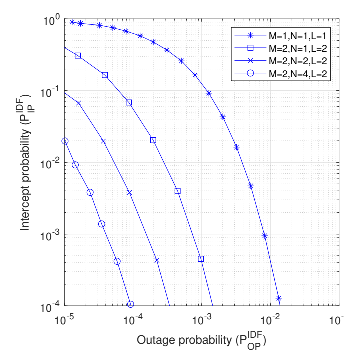


Fig. 10: SRT trade-off for IDF signaling for different M, N, L

the secrecy outage. A novel power back-off technique was proposed that allows a trade-off of outage for better secrecy. Finally, we demonstrated the validity of the analytical results through computer simulations. The derived insights lend important insights into the secrecy performance of networks with self-sustaining machine-type devices.

Appendix A

Proof of Lemma 1: We substitute for I_{SR}, I_{SD}, I_{SE} from (9), (10), (11) and I_{SRD}, I_{SRE} from (17) in expression of $p_{os,1}$ defined in (18). Specifically, $p_{os,1}$ becomes

$$p_{os,1}^{IDF} = \Pr\{g_s g_{SD}\Omega_{SD} > \gamma_{th}/\beta_R, g_s g_{SE}\Omega_{SE} \geq \gamma_{th,e}/\beta_R, g_s \leq \alpha_s\} + \Pr\{\beta_s P_{sat} k_{SD} g_{SD}/N_o > \gamma_{th}, \beta_s P_{sat} k_{SE} g_{SE}/N_o > \gamma_{th,e}, g_s > \alpha_s\}. \quad (49)$$

In case of multiple antenna, PDFs of channels g_{SD} and g_{SE} will be $f_{g_{SD}}(g_{SD}) = e^{-g_{SD}} g_{SD}^{N-1}/\Gamma(N)$ and $f_{g_{SE}}(g_{SE}) = e^{-g_{SE}} g_{SE}^{L-1}/\Gamma(N)$ respectively. Conditioning on the channel gain g_s, solving, and then averaging over g_s, we get

$$p_{os,1}^{IDF} = \int_0^{\alpha_s} \Gamma(N, \gamma_{th}/(g_s\Omega_{SD}))\Gamma(L, \gamma_{th,e}/(g_s\Omega_{SE})) f_{g_s}(g_s) dg_s + \int_{\alpha_s}^{\infty} \Gamma(N, \lambda_{SD}/\beta_R)\Gamma(L, \lambda_{SE}/\beta_R) f_{g_s}(g_s) dg_s. \quad (50)$$

Since the power beacon B possesses M antennas, the PDF of channel g_s and g_R will be $f_{g_s}(g_s) = \frac{e^{-g_s} g_s^{M-1}}{\Gamma(M)}$. Using the PDF of g_s and series expansion of lower incomplete gamma function [31, 8.352], we can express the above equation as

$$p_{os,1}^{IDF}=\sum_{m=0}^{N-1}\sum_{l=0}^{L-1}\int_0^{\alpha_S}\frac{\gamma_{th}^m\gamma_{th,e}^l}{g_S^{m+l}\Omega_{SD}^m\Omega_{SE}^l}\frac{e^{-\frac{\gamma_{th}}{g_S\Omega_{SD}}-\frac{\gamma_{th,e}}{g_S\Omega_{SE}}-g_S}g_S^{M-1}}{m!l!\Gamma(M)}dg_S$$
$$+\int_{\alpha_S}^{\infty}\Gamma(N,\lambda_{SD}/\beta_R)\Gamma(L,\lambda_{SE}/\beta_R)\frac{e^{-g_S}g_S^{M-1}}{\Gamma(M)}dg_S. \tag{51}$$

To evaluate $p_{os,2}^{IDF}$, we simplify the expression using the identity $\Pr\{A\bigcup B\}=\Pr\{A\}+\Pr\{B\}-\Pr\{A\cap B\}$ for events A and B. Using this in (19), we get

$$p_{os,2}^{IDF}=\underbrace{\Pr\{(I_{SR}\geq R_t),(I_{SRD}<R_t)\}}_{p_{os,21}^{IDF}}$$
$$+\underbrace{\Pr\{(I_{SD}<R_t),(I_{SR}\geq R_t),(I_{SRE}\geq R_e)\}}_{p_{os,22}^{IDF}}$$
$$-\underbrace{\Pr\{(I_{SD}<R_t),(I_{SR}\geq R_t),(I_{SRD}<R_t),(I_{SRE}\geq R_e)\}}_{p_{os,23}^{IDF}}. \tag{52}$$

Substituting for I_{SD}, I_{SR}, I_{SRD} and I_{SRE}, then conditioning $p_{os,2}$ on g_S, g_R, and exploiting independence of g_{SD}, g_{SR}, g_{SE} and g_{RE} we have

$$p_{os,2|I}^{IDF}=\underbrace{\Pr\{g_S g_{SD}\Omega_{SD}<\gamma_{th},X<\gamma_{th}\}}_{p_1|g_S,g_R}\underbrace{\Pr\{g_S g_{SR}\Omega_{SR}\geq\gamma_{th}\}}_{p_2|g_S}$$
$$+\underbrace{\Pr\{g_S g_{SD}\Omega_{SD}<\gamma_{th}\}}_{p_4|g_S}\Pr\{g_S g_{SR}\Omega_{SR}\geq\gamma_{th}\}\underbrace{\Pr\{Y\geq\gamma_{th,e}\}}_{p_3|g_S,g_R}$$
$$-\Pr\left\{g_S g_{SD}<\frac{\gamma_{th}}{\Omega_{SD}},X<\gamma_{th}\right\}\Pr\left\{g_S g_{SR}\geq\frac{\gamma_{th}}{\Omega_{SR}}\right\}\Pr\{Y\geq\gamma_{th,e}\}, \tag{53}$$

where $X=g_S g_{SD}\Omega_{SD}+g_R g_{RD}\Omega_{RD}$, $Y=g_S g_{SE}\Omega_{SE}+g_R g_{RE}\Omega_{RE}$. Since $p_{os,22|g_S,g_R}^{IDF}=p_{4|g_S}p_{2|g_S}p_{3|g_S,g_R}$, and $p_{os,23|g_S,g_R}^{IDF}=p_{1|g_S,g_R}p_{2|g_S}p_{3|g_S,g_R}$, $p_{os,2|g_S,g_R}^{IDF}=p_{os,21|g_S}^{IDF}+(p_{4|g_S}-p_{1|g_S,g_R})p_{2|g_S}p_{3|g_S,g_R}$. Therefore, for single antenna system ($M=1$, $N=1$, $L=1$), we have

$$p_1|g_S,g_R=1-\frac{g_R\Omega_{RD}e^{-\frac{\gamma_{th}}{g_R\Omega_{RD}}}}{(g_R\Omega_{RD}-g_S\Omega_{SD})}+\frac{g_S\Omega_{SD}e^{-\frac{\gamma_{th}}{g_S\Omega_{SD}}}}{(g_R\Omega_{RD}-g_S\Omega_{SD})},p_2|g_S=e^{-\frac{\gamma_{th}}{g_S\Omega_{SR}}},$$
$$p_3|g_S,g_R=\frac{g_R\Omega_{RE}e^{-\frac{\gamma_{th,e}}{g_R\Omega_{RE}}}-g_S\Omega_{SE}e^{-\frac{\gamma_{th,e}}{g_S\Omega_{SE}}}}{(g_R\Omega_{RE}-g_S\Omega_{SE})},p_4|g_S=1-e^{-\frac{\gamma_{th}}{g_S\Omega_{SD}}}. \tag{54}$$

Using the linear approximation to the exponential terms $e^{-x}\approx 1/(1+x)$, we can write $p_{4|g_S}=1-\frac{g_S}{\left(g_S+\frac{\gamma_{th}}{\Omega_{SD}}\right)}$, and $p_{1|g_S,g_R}=1-\frac{\left(g_S g_R\tau+\frac{\gamma_{th}g_R\tau}{\Omega_{SD}}+\frac{\gamma_{th}g_S}{\Omega_{SD}}\right)}{\left(g_S+\frac{\gamma_{th}}{\Omega_{SD}}\right)\left(g_R\tau+\frac{\gamma_{th}}{\Omega_{SD}}\right)}$ from (54) ($\tau=(1-\nu)^m$, defined in the text following (39)). We make the observation that $g_S g_R\tau\gg\frac{\gamma_{th}g_S}{\Omega_{SD}}$ and $g_S g_R\tau\gg\frac{\gamma_{th}g_R\tau}{\Omega_{SD}}$ since $g_S,g_R\gg\frac{\gamma_{th}}{\Omega_{SD}}$ for large SNR. So, $g_S g_R\tau+\frac{\gamma_{th}g_R\tau}{\Omega_{SD}}+\frac{\gamma_{th}g_S}{\Omega_{SD}}\approx g_S g_R\tau+\frac{\gamma_{th}g_S}{\Omega_{SD}}$. Hence, $p_{4|g_S}\approx p_{1|g_S,g_R}$. So, $p_{os,22}^{IDF}\approx p_{os,23}^{IDF}$, resulting in $p_{os,2}^{IDF}\approx p_{os,21}^{IDF}$. Similarly, we can show a similar result for multiple antennas. To evaluate $p_{os,21}^{IDF}$ we first derive the PDF for random variable $X=g_S g_{SD}\Omega_{SD}+g_R g_{RD}\Omega_{RD}$ to evaluate $p_{os,21}$ as

$$f_{X|g_S,g_R}(x)=\int_0^x f_{g_{SD}}(g_{SD})f_{g_{RD}}(x-g_{SD})dg_{SD}. \tag{55}$$

Using the PDF of g_{SD} and g_{RD} and conditioning on g_S and g_R, we get

$$f_{X|g_S,g_R}(x)=\int_0^x\frac{g_{SD}^{N-1}(x-g_{SD})^{N-1}e^{-\frac{x}{g_R\Omega_{RD}}-\frac{g_{SD}}{(g_S\Omega_{SD}-g_R\Omega_{RD})}}dg_{SD}}{(g_S g_R\Omega_{SD}\Omega_{RD})^N\Gamma^2(N)}. \tag{56}$$

Using the binomial expansion in the integral and rearranging terms, we get

$$f_{X|g_S,g_R}(x)=\frac{\sum_{r=0}^{N-1}\binom{N-1}{r}x^r(-1)^{N-1-r}e^{-\frac{x}{g_R\Omega_{RD}}}}{(g_S g_R\Omega_{SD}\Omega_{RD})^N\Gamma^2(N)}$$
$$\times\int_0^x g_{SD}^{2N-2-r}e^{-\frac{g_{SD}}{(g_S\Omega_{SD}-g_R\Omega_{RD})}}dg_{SD}. \tag{57}$$

Further, using the definition of the lower incomplete gamma function [32, 6.5.1], we get

$$f_{X|g_S,g_R}(x)=\frac{\sum_{r=0}^{N-1}\binom{N-1}{r}x^r(-1)^{N-1-r}e^{-\frac{x}{g_R\Omega_{RD}}}}{\Gamma^2(N)(g_R\Omega_{RD}-g_S\Omega_{SD})^{(2N-r-1)}}$$
$$\times(g_S\Omega_{SD}g_R\Omega_{RD})^{(N-r-1)}\gamma\left(2N-r-1,\frac{x(g_R\Omega_{RD}-g_S\Omega_{SD})}{g_S\Omega_{SD}g_R\Omega_{RD}}\right). \tag{58}$$

Using the series form of lower incomplete gamma function for integer values [31, 8.352] in the above expression, we obtain the PDF of X as

$$f_{X|g_S,g_R}(x)=\frac{e^{-\frac{x}{g_R\Omega_{RD}}}}{\Gamma^2(N)}\sum_{r=0}^{N-1}\binom{N-1}{r}x^r(-1)^{N-1-r}\Gamma(2N-r)$$
$$\times\frac{(g_S g_R\Omega_{SD}\Omega_{RD})^{N-r-1}}{(g_R\Omega_{RD}-g_S\Omega_{SD})^{(2N-r-1)}}-\frac{e^{-\frac{x}{g_R\Omega_{RD}}}}{\Gamma^2(N)}\sum_{r=0}^{N-1}\binom{N-1}{r}$$
$$\times x^r(-1)^{N-1-r}\frac{(g_S g_R\Omega_{SD}\Omega_{RD})^{N-r-1}\gamma(2N-r)}{(g_R\Omega_{RD}-g_S\Omega_{SD})^{(2N-r-1)}}$$
$$\times e^{-\frac{x(g_R\Omega_{RD}-g_S\Omega_{SD})}{g_S\Omega_{SD}g_R\Omega_{RD}}}\sum_{k=0}^{2N-r-2}\frac{x^k(g_R\Omega_{RD}-g_S\Omega_{SD})^k}{(g_S\Omega_{SD}g_R\Omega_{RD})^k k!}. \tag{59}$$

Using PDF of X in (97) and averaging over g_S and g_R, we get (22). Similarly, we can evaluate $p_{os,21|II}^{IDF}$, $p_{os,21|III}^{IDF}$ and $p_{os,21|IV}^{IDF}$ to obtain (24), (25) and (26) respectively. Expression of $p_{os,3}$ from (18) will be

$$p_{os,3}^{IDF}=\Pr\{g_S g_{SD}\Omega_{SD}<\gamma_{th}/\beta_R,g_S g_{SR}\Omega_{SR}<\gamma_{th}/\beta_R,g_S\leq\alpha_S\}$$
$$+\Pr\{\beta_S P_{sat}k_{SD}g_{SD}/N_o<\gamma_{th},\beta_S P_{sat}k_{SR}g_{SR}/N_o<\gamma_{th},g_S>\alpha_S\}. \tag{60}$$

Using PDF of channels g_{SD}, g_{SR} and conditioning on the channel gain g_S, solving, and then averaging on g_S, we get

$$p_{os,3}^{IDF}=\int_0^{\alpha_S}\gamma(N,\gamma_{th}/(g_S\Omega_{SD}))e^{-\frac{\gamma_{th}}{g_S\Omega_{SR}}}\frac{e^{-g_S}g_S^{M-1}}{\Gamma(M)}dg_S$$
$$+\int_{\alpha_S}^{\infty}\gamma(N,\lambda_{SD}/\beta_R)(1-e^{-\frac{\lambda_{SR}}{\beta_R}})\frac{e^{-g_S}g_S^{M-1}}{\Gamma(M)}dg_S. \tag{61}$$

Using the series expansion of lower incomplete gamma function [31, 8.352], we get $p_{os,3}^{IDF}$ in (20)

Appendix B

Proof of Lemma 3: Substituting $M=1,N=1,L=1$ in $p_{os,1}^{IDF}$ derived for multi-antennas in (51), $\frac{\Gamma(M,\alpha)}{\Gamma(L)\Gamma(N)}=e^{-\alpha}$, $\Gamma(N,\lambda_{SD}/\beta_R)=e^{-\lambda_{SD}/\beta_R}$ and $\Gamma(L,\lambda_{SE}/\beta_R)=e^{-\lambda_{SE}/\beta_R}$. Hence $p_{os,1}^{IDF}$ reduces to (35). To derive $p_{os,2|I}^{IDF}$ in (36), we use (53) and (54) to get $p_{os,21|I}^{IDF}$ in (38). Similarly, we can derive $p_{os,21|II}^{IDF}$, $p_{os,21|III}^{IDF}$ and $p_{os,21|IV}^{IDF}$. $p_{os,3}^{IDF}$ expression in (37) is achieved by substituting $N=1$ and $M=1$ in (61).

Appendix C

Proof of Lemma 4: $p_{os,1}$ in (35) reduces to $\sqrt{\frac{4\gamma_{th}}{\Omega_{SD}}+\frac{4\gamma_{th,e}}{\Omega_{SE}}}K_1\left(\sqrt{\frac{4\gamma_{th}}{\Omega_{SD}}+\frac{4\gamma_{th,e}}{\Omega_{SE}}}\right)$ and $p_{os,3}$ in (36) reduces to $1-\sqrt{\frac{4\gamma_{th}}{\Omega_{SD}}}K_1\left(\sqrt{\frac{4\gamma_{th}}{\Omega_{SD}}}\right)-\sqrt{\frac{4\gamma_{th}}{\Omega_{SR}}}K_1\left(\sqrt{\frac{4\gamma_{th}}{\Omega_{SR}}}\right)+\sqrt{\frac{4\gamma_{th}}{\Omega}}K_1\left(\sqrt{\frac{4\gamma_{th}}{\Omega}}\right)$ for large value of α (at high SNR). Further, $p_{os,2}^{IDF}\approx p_{os,21}^{IDF}$ (see paragraph succeeding (54)). To simplify $p_{os,21}^{IDF}$, we use linear approximation of $e^{-\frac{\gamma_{th}}{g_S\Omega_{SR}}}\approx\left(1+\gamma_{th}/g_S\Omega_{SR}\right)^{-1}$,

$e^{-\frac{\gamma_{th}}{g_S\Omega_{SD}}} \approx \left(1+\gamma_{th}/g_S\Omega_{SD}\right)^{-1}$ and $e^{-\frac{\gamma_{th}}{g_R\Omega_{RD}}} \approx \left(1+\gamma_{th}/g_R\Omega_{RD}\right)^{-1}$ in $p_{os,21|I}$ (defined in (38)). Simplifying further, we get

$$p_{os,21|I} \approx \int_0^{\alpha_S}\int_0^{\alpha_R} \frac{e^{-g_R-g_S}dg_S dg_R}{(1+\gamma_{th}/g_S\Omega_{SR})}\left[1-\frac{g_S g_R+\gamma_{th}g_S/\Omega_{RD}+\gamma_{th}g_R/\Omega_{SD}}{(\gamma_{th}/\Omega_{SD}+g_S)(\gamma_{th}/\Omega_{RD}+g_R)}\right]$$
$$=\int_0^{\alpha_S}\int_0^{\alpha_R} \frac{\gamma_{th}^2\Omega_{SR}e^{-g_R-g_S}g_S dg_R dg_S}{(g_S\Omega_{SR}+\gamma_{th})(\gamma_{th}+g_S\Omega_{SD})(\gamma_{th}+g_R\Omega_{RD})}. \quad (62)$$

Using partial fractions of terms involving $(g_S\Omega_{SD}+\gamma_{th})$ and $(g_S\Omega_{SR}+\gamma_{th})$ and using the identity [32, 5.1.28], we obtain $p_{os,21|I}$ in (39). Similarly, we can find $p_{os,21|II}$ and $p_{os,21|III}$.

Appendix D

Proof of Lemma 5: In order to prove the convexity of p_{os} with P for IDF signalling, we write the expression for $p^{IDF}_{os.,approx.}$ in (40) as a function of $\rho = \frac{P}{N_o}$ as follows

$$p^{IDF}_{os,approx.}(\rho) = 1+\beta_1'\rho^{-1/2}K_1\left(\beta_1'\rho^{-1/2}\right)-\beta_2'\rho^{-1/2}K_1\left(\beta_2'\rho^{-1/2}\right)$$
$$-\beta_3'\rho^{-1/2}K_1\left(\beta_3'\rho^{-1/2}\right)+\beta_4'\rho^{-1/2}K_1\left(\beta_4'\rho^{-1/2}\right)$$
$$+\underbrace{(q_1'/\rho^2)e^{\frac{\gamma_{th}}{\rho\Omega_{SD}'}}E_1(\gamma_{th}/\rho\Omega_{SD}')e^{\frac{\gamma_{th}}{\rho\Omega_{RD}'}}E_1(\gamma_{th}/\rho\Omega_{RD}')}_{Q_1}$$
$$-\underbrace{(q_2'/\rho^2)e^{\frac{\gamma_{th}}{\rho\Omega_{SR}'}}E_1(\gamma_{th}/\rho\Omega_{SR}')e^{\frac{\gamma_{th}}{\rho\Omega_{RD}'}}E_1(\gamma_{th}/\rho\Omega_{RD}')}_{Q_2}, \quad (63)$$

where $\beta_1' = \sqrt{\frac{4\gamma_{th}}{\Omega_{SD}'}+\frac{4\gamma_{th,e}}{\Omega_{SE}'}}$, $\beta_2' = \sqrt{\frac{4\gamma_{th}}{\Omega_{SD}'}}$, $\beta_3' = \sqrt{\frac{4\gamma_{th}}{\Omega_{SR}'}}$, $\beta_4' = \sqrt{\frac{4\gamma_{th}}{\Omega'}}$, $\Omega_{SD}' = \frac{\beta_S k_S k_{SD}}{\beta_R}$, $\Omega_{SR}' = \frac{\beta_S k_S k_{SR}}{\beta_R}$, $\Omega_{RD}' = k_R k_{SD}$, $\Omega_{SE}' = \frac{\beta_S k_S k_{SE}}{\beta_R}$, $\Omega' = \frac{\Omega_{SR}'\Omega_{SD}'}{(\Omega_{SR}'+\Omega_{SD}')}$, $q_1' = \frac{\gamma_{th}^2\Omega_{SR}'}{\Omega_{SD}'\Omega_{RD}'(\Omega_{SR}'-\Omega_{SD}')}$, and $q_2' = \frac{\gamma_{th}^2}{\Omega_{RD}'(\Omega_{SR}'-\Omega_{SD}')}$. We find derivatives of each term in (63). We use properties of derivative of Bessel function [32, 9.6.27, 9.6.29] to find derivative of terms involving Bessel function in (63). We also define $T_j(\rho) = e^{\frac{\gamma_{th}}{\rho\Omega_j'}}E_1(\frac{\gamma_{th}}{\rho\Omega_j'})e^{\frac{\gamma_{th}}{\rho\Omega_{RD}'}}E_1(\frac{\gamma_{th}}{\rho\Omega_{RD}'})$, $j\in\{SR,SD\}$ to find derivative of terms Q_1 and Q_2 by using [32, 5,1.26]. For $i\in\{1,2,3,4\}$,

$$\frac{d(\beta_i'\rho^{-1/2}K_1(\beta_i'\rho^{-1/2}))}{d\rho} = -\frac{\beta_i'K_1(\beta_i'\rho^{-1/2})}{2\rho^{3/2}}+\frac{\beta_i'^2K_0(\beta_i'\rho^{-1/2})}{4\rho^2}$$
$$+\frac{\beta_i'^2K_2(\beta_i'\rho^{-1/2})}{4\rho^2}, \quad (64)$$

$$\frac{d^2(\beta_i'\rho^{-1/2}K_1(\beta_i'\rho^{-1/2}))}{d\rho^2} = -(5/8)\beta_i'^2\rho^3K_0(\beta_i'\rho^{-1/2})$$
$$+\left((3/4)\beta_i'\rho^{-5/2}+(1/8)\beta_i'^2\rho^{-7/2}+(1/16)\beta_i'^3\rho^{-7/2}\right)K_1(\beta_i'\rho^{-1/2})$$
$$-(5/8)\beta_i'^2\rho^{-3}K_2(\beta_i'\rho^{-1/2})+(1/16)\beta_i'^3\rho^{-7/2}K_3(\beta_i'\rho^{-1/2}), \quad (65)$$

$$T_j'(\rho) = \frac{dT_j(\rho)}{d\rho} =$$
$$\frac{1}{\rho}e^{\frac{\gamma_{th}}{\rho\Omega_j'}}E_1(\frac{\gamma_{th}}{\rho\Omega_j'})+\frac{1}{\rho}e^{\frac{\gamma_{th}}{\rho\Omega_{RD}'}}E_1(\frac{\gamma_{th}}{\rho\Omega_{RD}'})-\frac{\gamma_{th}T_0(\rho)}{\rho^2\Omega_{RD}'}+\frac{\gamma_{th}T_0(\rho)}{\rho^2\Omega_j'}, \quad (66)$$

$$\frac{dQ_1}{d\rho} = \frac{q_1'T_{SD}'(\rho)}{\rho^2}-\frac{2q_1'T_{SD}(\rho)}{\rho^3}, \frac{dQ_2}{d\rho} = \frac{q_2'T_{SR}'(\rho)}{\rho^2}-\frac{2q_2'T_{SR}(\rho)}{\rho^3},$$
$$\frac{d^2Q_1}{d\rho^2} = \frac{q_1'T_{SD}'(\rho)}{\rho^2}-\frac{2q_1'T_{SD}(\rho)}{\rho^3}, \frac{d^2Q_2}{d\rho^2} = \frac{q_2'T_{SR}'(\rho)}{\rho^2}-\frac{2q_2'T_{SR}(\rho)}{\rho^3}. \quad (67)$$

Equating $\frac{dp^{IDF}_{os,approx.}}{d\rho}$ to zero using the above terms, P^* can be evaluated. However numerical methods are required due to the complex nature of the equation. Further, it can be shown that $\frac{d^2p^{IDF}_{os,approx.}}{d\rho^2}|_{P=P^*} > 0$.

Appendix E

Proof of Lemma 6 and 7: **Proof of convexity with β_R:** Using the expressions of $p^{IDF}_{os,22} = p_{4|g_S}p_{2|g_S}p_{3|g_S,g_R}$ and $p_{os,23} = p_{1|g_S}p_{2|g_S}p_{3|g_S}$ from paragraph succeeding (53). we derive approximations for $p^{IDF}_{os,22}$ and $p^{IDF}_{os,23}$ using linear approximation to $e^{-\frac{\gamma_{th,e}}{g_R\Omega_{RE}}} \approx (1+\gamma_{th,e}/g_R\Omega_{RE})^{-1}$, $e^{-\frac{\gamma_{th,e}}{g_S\Omega_{SE}}} \approx (1+\gamma_{th,e}/g_S\Omega_{SE})^{-1}$, $e^{-\frac{\gamma_{th}}{g_S\Omega_{SD}}} \approx (1+\gamma_{th}/g_S\Omega_{SD})^{-1}$, $e^{-\frac{\gamma_{th}}{g_R\Omega_{RD}}} \approx (1+\gamma_{th}/g_R\Omega_{RD})^{-1}$, and $e^{-\frac{\gamma_{th}}{g_S\Omega_{SR}}} \approx (1+\gamma_{th}/g_S\Omega_{SR})^{-1}$ in (53) and (54). We then simplify the resulting expressions by segregating terms involving g_S and g_R using partial fractions, then individually integrate over g_S and g_R to obtain following expressions

$$p^{IDF}_{os,22} \approx -1+v_{21}e^{\frac{\gamma_{th}}{\Omega}}E_1\left(\frac{\gamma_{th}}{\Omega}\right)+v_{22}e^{\frac{\gamma_{th,e}}{\Omega_{RE}}}E_1\left(\frac{\gamma_{th,e}}{\Omega_{RE}}\right)e^{\frac{\gamma_{th,e}}{\Omega}}E_1(\frac{\gamma_{th,e}}{\Omega})$$
$$-v_{23}e^{\frac{\gamma_{th,e}}{\Omega_{RE}}}E_1\left(\frac{\gamma_{th,e}}{\Omega_{RE}}\right)e^{\frac{\gamma_{th,e}}{\Omega_{SE}}}E_1\left(\frac{\gamma_{th,e}}{\Omega_{SE}}\right), \quad (68)$$

$$p^{IDF}_{os,23} \approx -1+v_{31}e^{\frac{\gamma_{th}}{\Omega_{SR}}}E_1(\frac{\gamma_{th}}{\Omega_{SR}})$$
$$+(v_{32}-v_{36})e^{\frac{\gamma_{th}}{\Omega_{SD}}}E_1(\frac{\gamma_{th}}{\Omega_{SD}})e^{\frac{\gamma_{th}}{\Omega_{RD}}}E_1(\frac{\gamma_{th}}{\Omega_{RD}})$$
$$-(v_{33}-v_{37})e^{\frac{\gamma_{th}}{\Omega_{SR}}}E_1(\frac{\gamma_{th}}{\Omega_{SR}})e^{\frac{\gamma_{th}}{\Omega_{RD}}}E_1(\frac{\gamma_{th}}{\Omega_{RD}})$$
$$+(v_{34}-v_{36}+v_{37})e^{\frac{\gamma_{th,e}}{\Omega_{SE}}}E_1(\frac{\gamma_{th,e}}{\Omega_{SE}})e^{\frac{\gamma_{th,e}}{\Omega_{RE}}}E_1(\frac{\gamma_{th,e}}{\Omega_{RE}})$$
$$-(v_{35}+v_{37})e^{\frac{\gamma_{th}}{\Omega_{SR}}}E_1(\frac{\gamma_{th}}{\Omega_{SR}})e^{\frac{\gamma_{th,e}}{\Omega_{RE}}}E_1(\frac{\gamma_{th,e}}{\Omega_{RE}})$$
$$+v_{36}e^{\frac{\gamma_{th}}{\Omega_{SD}}}E_1(\frac{\gamma_{th}}{\Omega_{SD}})e^{\frac{\gamma_{th,e}}{\Omega_{RE}}}E_1(\frac{\gamma_{th,e}}{\Omega_{RE}})$$
$$+(v_{36}-v_{37})e^{\frac{\gamma_{th,e}}{\Omega_{SE}}}E_1(\frac{\gamma_{th,e}}{\Omega_{SE}})e^{\frac{\gamma_{th}}{\Omega_{RD}}}E_1(\frac{\gamma_{th}}{\Omega_{RD}}), \quad (69)$$

where $\Omega = \frac{\Omega_{SR}\Omega_{SD}}{(\Omega_{SR}+\Omega_{SD})}$, $v_{21} = \frac{\gamma_{th}}{\Omega}$, $v_{22} = \frac{\gamma_{th,e}^2\gamma_{th}}{\Omega_{RE}(\gamma_{th}\Omega_{SE}-\gamma_{th,e}\Omega)}$, $v_{23} = v_{22}\frac{\gamma_{th,e}\Omega}{\gamma_{th}\Omega_{SE}}$, $v_{31} = \frac{\gamma_{th}}{\Omega_{SR}}$, $v_{32} = \frac{\gamma_{th}^2\Omega_{SR}}{\Omega_{SD}\Omega_{RD}(\Omega_{SR}-\Omega_{SD})}$, $v_{33} = v_{32}\frac{\Omega_{SD}}{\Omega_{SR}}$, $v_{34} = \frac{\gamma_{th,e}^3\Omega_{SR}}{\Omega_{SE}\Omega_{RE}(\gamma_{th,e}\Omega_{SR}-\gamma_{th}\Omega_{SE})}$, $v_{35} = v_{34}\frac{\gamma_{th}\Omega_{SE}}{\gamma_{th,e}\Omega_{SR}}$, $v_{36} = \frac{\gamma_{th}^2\gamma_{th,e}^2\Omega_{SR}}{(\Omega_{SR}-\Omega_{SD})(\gamma_{th,e}\Omega_{SD}-\gamma_{th}\Omega_{SE})(\gamma_{th,e}\Omega_{RD}-\gamma_{th}\Omega_{RE})}$, and $v_{37} = v_{36}\frac{(\gamma_{th,e}\Omega_{SD}-\gamma_{th}\Omega_{SE})}{(\gamma_{th,e}\Omega_{SR}-\gamma_{th}\Omega_{SE})}$.

Expressions of $p^{IDF}_{os,1}(\beta_S,\beta_R)$ and $p^{IDF}_{os,3}(\beta_S,\beta_R)$ are

$$p^{IDF}_{os,1}(\beta_S,\beta_R) = \tilde{\beta}_1\beta_S^{-1/2}K_1(\tilde{\beta}_1\beta_S^{-1/2}), \quad (70)$$
$$p^{IDF}_{os,3}(\beta_S,\beta_R) = 1-\tilde{\beta}_2\beta_S^{-1/2}K_1(\tilde{\beta}_2\beta_S^{-1/2})$$
$$-\tilde{\beta}_3\beta_S^{-1/2}K_1(\tilde{\beta}_3\beta_S^{-1/2})+\tilde{\beta}_4\beta_S^{-1/2}K_1(\tilde{\beta}_4\beta_S^{-1/2}), \quad (71)$$

where $\tilde{\beta}_1 = \sqrt{\frac{4\tilde{\gamma_{th}}}{\tilde{\Omega}_{SD}}+\frac{4\tilde{\gamma_{th,e}}}{\tilde{\Omega}_{SE}}}$, $\tilde{\beta}_2 = \sqrt{\frac{4\tilde{\gamma_{th}}}{\tilde{\Omega}_{SD}}}$, $\tilde{\beta}_3 = \sqrt{\frac{4\tilde{\gamma_{th}}}{\tilde{\Omega}_{SR}}}$, $\tilde{\beta}_4 = \sqrt{\frac{4\tilde{\gamma_{th}}}{\tilde{\Omega}_{SR}}+\frac{4\tilde{\gamma_{th,e}}}{\tilde{\Omega}_{SD}}}$, $\tilde{\gamma_{th}} = \frac{(2^{R_t}-1)}{\eta}$, $\tilde{\gamma_{th,e}} = \frac{(2^{R_e}-1)}{\eta}$, $\tilde{\Omega}_{SR} = \frac{Pk_Sk_{SR}}{N_o}$, $\tilde{\Omega}_{SD} = \frac{Pk_Sk_{SD}}{N_o}$, $\tilde{\Omega}_{RD} = \frac{Pk_Rk_{RD}}{N_o}$, $\tilde{\Omega}_{SE} = \frac{Pk_Sk_{SE}}{N_o}$, $\tilde{\Omega}_{RE} = \frac{Pk_Rk_{RE}}{N_o}$. In order to express $p^{IDF}_{os,2}(\beta_S,\beta_R)$, we define following terms

$$T_{SR} = \frac{1}{\beta_S}e^{\frac{\tilde{\gamma_{th}}}{\beta_S\tilde{\Omega}_{SR}}}E_1(\frac{\tilde{\gamma_{th}}}{\beta_S\tilde{\Omega}_{SR}}), \quad T_{SD} = \frac{1}{\beta_S}e^{\frac{\tilde{\gamma_{th}}}{\beta_S\tilde{\Omega}_{SD}}}E_1(\frac{\tilde{\gamma_{th}}}{\beta_S\tilde{\Omega}_{SD}}),$$

$$T_{SE}=\frac{1}{\beta_S}e^{\frac{\gamma_{\tilde{th},e}}{\beta_S\tilde{\Omega}_{SE}}}E_1(\frac{\gamma_{\tilde{th},e}}{\beta_S\tilde{\Omega}_{SE}}),\ \ T_O=\frac{1}{\beta_S}e^{\frac{\tilde{\gamma_{th}}}{\beta_S\tilde{\Omega}}}E_1(\frac{\tilde{\gamma_{th}}}{\beta_S\tilde{\Omega}}),$$
$$T_E=\frac{1}{\beta_S}e^{\frac{\gamma_{\tilde{th},e}}{\beta_S\tilde{\Omega}}}E_1(\frac{\gamma_{\tilde{th},e}}{\beta_S\tilde{\Omega}}),\ \ T_{RD}=\frac{1}{\beta_R}e^{\frac{\tilde{\gamma_{th}}}{\beta_R\tilde{\Omega}_{RD}}}E_1(\frac{\tilde{\gamma_{th}}}{\beta_R\tilde{\Omega}_{RD}}),$$
$$T_{RE}=\frac{1}{\beta_R}e^{\frac{\gamma_{\tilde{th},e}}{\beta_R\tilde{\Omega}_{RE}}}E_1(\frac{\gamma_{\tilde{th},e}}{\beta_R\tilde{\Omega}_{RE}}),\tag{72}$$

So, the expression of $p_{os,2}^{IDF}(\beta_S,\beta_R)$ with aforementioned terms will be

$$p_{os,2}^{IDF}(\beta_S,\beta_R)\approx b_1T_{SR}T_{RD}-b_2T_{SD}T_{RD}+b_3T_O-b_4T_{SR}+b_5T_OT_{RE}$$
$$-b_6T_{SE}T_{RE}-b_7T_{SR}T_{RE}-b_8T_{SE}T_{RD}-b_9T_{SD}T_{RE},\tag{73}$$

where $b_1=\tilde{q}_1+\tilde{v}_{33}-\tilde{v}_{37}$, $b_2=\tilde{q}_2+\tilde{v}_{32}-\tilde{v}_{36}$, $b_3=\tilde{v}_{21}$, $b_4=\tilde{v}_{31}$, $b_5=\tilde{v}_{22}$, $b_6=\tilde{v}_{23}+\tilde{v}_{34}-\tilde{v}_{36}+\tilde{v}_{37}$, $b_7=-\tilde{v}_{35}-\tilde{v}_{37}$, $b_8=\tilde{v}_{36}-\tilde{v}_{37}$, $b_9=\tilde{v}_{36}$, $\tilde{q}_1=\frac{\tilde{\gamma_{th}^2}}{\tilde{\Omega}_{RD}(\tilde{\Omega}_{SD}-\tilde{\Omega}_{SR})}$, $\tilde{q}_2=\frac{\tilde{\gamma_{th}}^2\tilde{\Omega}_{SR}}{\tilde{\Omega}_{SD}\tilde{\Omega}_{RD}(\tilde{\Omega}_{SD}-\tilde{\Omega}_{SR})}$, $\tilde{v}_{21}=\frac{\tilde{\gamma_{th}}}{\tilde{\Omega}}$, $\tilde{v}_{22}=\frac{\gamma_{\tilde{th},e}{}^2\tilde{\gamma_{th}}}{\tilde{\Omega}_{RE}(\tilde{\gamma_{th}}\tilde{\Omega}_{SE}-\gamma_{\tilde{th},e}\tilde{\Omega})}$, $\tilde{v}_{23}=\tilde{v}_{22}\frac{\gamma_{th,e}\tilde{\Omega}}{\gamma_{th}\tilde{\Omega}_{SE}}$, $\tilde{v}_{31}=\frac{\tilde{\gamma_{th}}}{\tilde{\Omega}_{SR}}$, $\tilde{v}_{32}=\frac{\tilde{\gamma_{th}}^2\tilde{\Omega}_{SR}}{\tilde{\Omega}_{SD}\tilde{\Omega}_{RD}(\tilde{\Omega}_{SR}-\tilde{\Omega}_{SD})}$, $\tilde{v}_{33}=\tilde{v}_{32}\frac{\tilde{\Omega}_{SD}}{\tilde{\Omega}_{SR}}$, $\tilde{v}_{34}=\frac{\gamma_{\tilde{th}_e}^3\tilde{\Omega}_{SR}}{\tilde{\Omega}_{SE}\tilde{\Omega}_{RE}(\gamma_{\tilde{th},e}\tilde{\Omega}_{SR}-\tilde{\gamma_{th}}\tilde{\Omega}_{SE})}$, $\tilde{v}_{35}=\tilde{v}_{34}\frac{\tilde{\gamma_{th}}\tilde{\Omega}_{SE}}{\gamma_{\tilde{th},e}\tilde{\Omega}_{SR}}$, $\tilde{v}_{36}=\frac{\tilde{\gamma_{th}}^2\gamma_{\tilde{th},e}{}^2\tilde{\Omega}_{SR}}{(\tilde{\Omega}_{SR}-\tilde{\Omega}_{SD})(\gamma_{\tilde{th},e}\tilde{\Omega}_{SD}-\tilde{\gamma_{th}}\tilde{\Omega}_{SE})(\gamma_{\tilde{th},e}\tilde{\Omega}_{RD}-\tilde{\gamma_{th}}\tilde{\Omega}_{RE})}$, $\tilde{v}_{37}=\tilde{v}_{36}\frac{(\gamma_{\tilde{th},e}\tilde{\Omega}_{SD}--\tilde{\gamma_{th}}\tilde{\Omega}_{SE})}{(\gamma_{\tilde{th},e}\tilde{\Omega}_{SR}-\tilde{\gamma_{th}}\tilde{\Omega}_{SE})}$.

We establish convexity with β_R by finding $\frac{d^2p_{os,1}^{IDF}(\beta_S,\beta_R)}{d\beta_R^2}$, $\frac{d^2p_{os,3}^{IDF}(\beta_S,\beta_R)}{d\beta_R^2}$ and $\frac{d^2p_{os,2}^{IDF}(\beta_S,\beta_R)}{d\beta_R^2}$ using (70), (71), and (73) respectively.

$$\frac{d^2p_{os,1}^{IDF}(\beta_S,\beta_R)}{d\beta_R^2}=0,\qquad\frac{d^2p_{os,3}^{IDF}(\beta_S,\beta_R)}{d\beta_R^2}=0,\tag{74}$$
$$\frac{d^2p_{os,2}^{IDF}(\beta_S,\beta_R)}{d\beta_R^2}\approx b_1T_{SR}\frac{d^2T_{RD}}{d\beta_R^2}-b_2T_{SD}\frac{d^2T_{RD}}{d\beta_R^2}+b_5T_O\frac{d^2T_{RE}}{d\beta_R^2}$$
$$-b_6T_{SE}\frac{d^2T_{RE}}{d\beta_R^2}-b_7T_{SR}\frac{d^2T_{RE}}{d\beta_R^2}-b_8T_{SE}\frac{d^2T_{RD}}{d\beta_R^2}-b_9T_{SD}\frac{d^2T_{RE}}{d\beta_R^2}.\tag{75}$$

We find $\frac{d^2T_{RD}}{d\beta_R^2}$ and $\frac{d^2T_{RE}}{d\beta_R^2}$ using [32, 5.1.26] as follows:

$$\frac{dT_{RD}}{d\beta_R}=-\Big(\frac{1}{\beta_R^2}+\frac{\tilde{\gamma_{th}}}{\tilde{\Omega}_{RD}\beta_R^3}\Big)T_{RD}+\frac{1}{\beta_R^2}\quad,\tag{76}$$

$$\frac{d^2T_{RD}}{d\beta_R^2}=-\Big(\frac{1}{\beta_R^4}+\frac{2\tilde{\gamma_{th}}}{\tilde{\Omega}_{RD}\beta_R^5}+\frac{2}{\beta_R^3}+\frac{3\tilde{\gamma_{th}}}{\tilde{\Omega}_{RD}\beta_R^4}+\frac{\tilde{\gamma_{th}}^2}{\tilde{\Omega}_{RD}\beta_R^6}\Big)T_{RD}$$
$$-\frac{1}{\beta_R^4}-\frac{\tilde{\gamma_{th}}}{\tilde{\Omega}_{RD}\beta_R^5}-\frac{2}{\beta_R^3},\tag{77}$$

$$\frac{dT_{RE}}{d\beta_R}=-\Big(\frac{1}{\beta_R^2}+\frac{\gamma_{\tilde{th},e}}{\tilde{\Omega}_{RE}\beta_R^3}\Big)T_{RE}+\frac{1}{\beta_R^2},$$
$$\frac{d^2T_{RE}}{d\beta_R^2}=-\Big(\frac{1}{\beta_R^4}+\frac{2\gamma_{\tilde{th},e}}{\tilde{\Omega}_{RE}\beta_R^5}+\frac{2}{\beta_R^3}+\frac{3\gamma_{\tilde{th},e}}{\tilde{\Omega}_{RE}\beta_R^4}+\frac{\gamma_{\tilde{th},e}{}^2}{\tilde{\Omega}_{RE}\beta_R^6}\Big)T_{RE}$$
$$-\frac{1}{\beta_R^4}-\frac{\gamma_{\tilde{th},e}}{\tilde{\Omega}_{RE}\beta_R^5}-\frac{2}{\beta_R^3}.\tag{78}$$

We further observe $b_5,b_6\gg b_1,b_2,b_7,b_8,b_9$. So, (75) can be approximated to obtain $\frac{d^2p_{os}^{IDF}(\beta_S,\beta_R)}{d\beta_R^2}$ as

$$\frac{d^2p_{os}^{IDF}(\beta_S,\beta_R)}{d\beta_R^2}=\frac{d^2p_{os,2}^{IDF}(\beta_S,\beta_R)}{d\beta_R^2}$$
$$\approx b_5T_O\frac{d^2T_{RE}}{d\beta_R^2}-b_6T_{SE}\frac{d^2T_{RE}}{d\beta_R^2}.\tag{79}$$

Further $T(x)=\frac{1}{\beta_S}e^xE_1(x)$ is decreasing function of x, $x\in\{\frac{\tilde{\gamma_{th}}}{\tilde{\Omega}\beta_S},\frac{\gamma_{\tilde{th},e}}{\tilde{\Omega}_{SE}}\}$. Since, $\frac{\tilde{\gamma_{th}}}{\tilde{\Omega}\beta_S}<\frac{\gamma_{\tilde{th},e}}{\tilde{\Omega}_{SE}\beta_S}$ (widely studied scenario in literature). Hence $T_O>T_{SE}$. Also, $b_6=b_5\frac{(\gamma_{\tilde{th},e}\tilde{\Omega_{SR}}-\gamma_{\tilde{th},e}\tilde{\Omega})}{(\gamma_{\tilde{th},e}\tilde{\Omega_{SR}}-\tilde{\gamma_{th}}\tilde{\Omega}_{SE})}$, resulting in $|b_5|\approx|b_6|$. Since, $b_5,b_6<0$ and $\frac{d^2T_{RE}}{d\beta_R^2}<0$ resulting in $\frac{d^2p_{os}^{IDF}}{d\beta_R^2}>0$.

Proof of convexity with β_S: In order to proof convexity of $p_{os,approx.}^{IDF}$ with β_S, we find $\frac{d^2p_{os,1}^{IDF}(\beta_S,\beta_R)}{d\beta_S^2}$, $\frac{d^2p_{os,3}^{IDF}(\beta_S,\beta_R)}{d\beta_S^2}$ and $\frac{d^2p_{os,2}^{IDF}(\beta_S,\beta_R)}{d\beta_S^2}$ using (70), (71), and (73) respectively. Expressions for $\frac{d^2p_{os,1}^{IDF}(\beta_S,\beta_R)}{d\beta_S^2}$ and $\frac{d^2p_{os,3}^{IDF}(\beta_S,\beta_R)}{d\beta_S^2}$ is expressed using following defined term S_i and its first and second derivative with β_S, $i\in\{1,2,3,4\}$ using [32, 9.6.27, 9.6.29].

$$S_i=\tilde{\beta}_i\beta_S^{-1/2}K_1(\tilde{\beta}_i\beta_S^{-1/2}),$$
$$\frac{dS_i}{d\beta_S}=-(1/2)\tilde{\beta}_i\beta_S^{-3/2}K_1(\tilde{\beta}_i\beta_S^{-1/2})+(1/4)\tilde{\beta}_i^2\beta_S^{-2}K_0(\tilde{\beta}_i\beta_S^{-1/2})$$
$$+(1/4)\tilde{\beta}_i^2\beta_S^{-2}K_2(\tilde{\beta}_i\beta_S^{-1/2}),$$
$$\frac{d^2S_i}{d\beta_S^2}=-(5/8)\tilde{\beta}_i\beta_S^{-3}K_1\left(\tilde{\beta}_i\beta_S^{-1/2}\right)+(3/4)\tilde{\beta}_i\beta_S^{-5/2}$$
$$+(1/16)\tilde{\beta}_i^3\beta_S^{-7/2}K_1\left(\tilde{\beta}_i\beta_S^{-1/2}\right)-(5/8)\tilde{\beta}_i^2\beta_S^{-3}K_2\left(\tilde{\beta}_i\beta_S^{-1/2}\right)$$
$$+(1/16)\tilde{\beta}_i^3\beta_S^{-7/2}K_3\left(\tilde{\beta}_i\beta_S^{-1/2}\right),\tag{80}$$

Hence,

$$\frac{d^2p_{os,1}^{IDF}}{d\beta_S^2}=\frac{d^2S_1}{d\beta_S^2},\qquad\frac{d^2p_{os,3}^{IDF}}{d\beta_S^2}=-\frac{d^2S_2}{d\beta_S^2}-\frac{d^2S_3}{d\beta_S^2}+\frac{d^2S_4}{d\beta_S^2},\tag{81}$$
$$\frac{d^2p_{os,2}^{IDF}}{d\beta_S^2}\approx b_1\frac{d^2T_{SR}}{d\beta_S^2}T_{RD}-b_2\frac{d^2T_{SD}}{d\beta_S^2}T_{RD}+b_3\frac{d^2T_O}{d\beta_S^2}-b_4\frac{d^2T_{SR}}{d\beta_S^2}$$
$$+b_5\frac{d^2T_O}{d\beta_S^2}T_{RE}-b_6\frac{d^2T_{SE}}{d\beta_S^2}T_{RE}-b_7\frac{d^2T_{SR}}{d\beta_S^2}T_{RE}-b_8\frac{d^2T_{SE}}{d\beta_S^2}T_{RD}$$
$$-b_9\frac{d^2T_{SD}}{d\beta_S^2}T_{RE}.\tag{82}$$

As before, we find $\frac{dT_i}{d\beta_S}$, $\frac{d^2T_i}{d\beta_S^2}$ for $i\in\{SR,SD,O\}$ and $\frac{dT_j}{d\beta_S}$, $\frac{d^2T_j}{d\beta_S^2}$ for $j\in\{SE,E\}$ using [32, 5.1.26] as follows

$$\frac{dT_i}{d\beta_S}=-\Big(\frac{1}{\beta_S^2}+\frac{\tilde{\gamma_{th}}}{\tilde{\Omega}_i\beta_S^3}\Big)T_i+\frac{1}{\beta_S^2},$$
$$\frac{d^2T_i}{d\beta_S^2}=-\Big(\frac{1}{\beta_S^4}+\frac{2\tilde{\gamma_{th}}}{\tilde{\Omega}_i\beta_S^5}+\frac{2}{\beta_S^3}+\frac{3\tilde{\gamma_{th}}}{\tilde{\Omega}_i\beta_S^4}+\frac{\tilde{\gamma_{th}}^2}{\tilde{\Omega}_i\beta_S^6}\Big)T_i$$
$$-\frac{1}{\beta_S^4}-\frac{\tilde{\gamma_{th}}}{\tilde{\Omega}_i\beta_S^5}-\frac{2}{\beta_S^3},i\in\{SR,SD,O\},\tag{83}$$

$$\frac{dT_j}{d\beta_S}=-\Big(\frac{1}{\beta_S^2}+\frac{\gamma_{\tilde{th},e}}{\tilde{\Omega}_j\beta_S^3}\Big)T_j+\frac{1}{\beta_S^2},$$
$$\frac{d^2T_j}{d\beta_S^2}=-\Big(\frac{1}{\beta_S^4}+\frac{2\gamma_{\tilde{th},e}}{\tilde{\Omega}_j\beta_S^5}+\frac{2}{\beta_S^3}+\frac{3\gamma_{\tilde{th},e}}{\tilde{\Omega}_j\beta_S^4}+\frac{\gamma_{\tilde{th},e}{}^2}{\tilde{\Omega}_j\beta_S^6}\Big)T_j$$
$$-\frac{1}{\beta_S^4}-\frac{\gamma_{\tilde{th},e}}{\tilde{\Omega}_j\beta_S^5}-\frac{2}{\beta_S^3},j\in\{SE,E\}.\tag{84}$$

We observe that $\frac{d^2 p_{os,2}^{IDF}}{d\beta_S^2} \gg \frac{d^2 p_{os,1}^{IDF}}{d\beta_S^2}, \frac{d^2 p_{os,3}^{IDF}}{d\beta_S^2}$. So, $\frac{d^2 p_{os}^{IDF}}{d\beta_S^2} \approx \frac{d^2 p_{os,2}^{IDF}}{d\beta_S^2}$. Also the terms involving b_1, b_5, b_8 are positive terms, among which $b_5 \gg b_1, b_8$. Hence the dominating positive term is $b_5 \frac{d^2 T_O}{d\beta_S^2} T_{RE}$. Similarly the dominating negative term is $b_3 \frac{d^2 T_O}{d\beta_S^2}$. So we can further approximate $\frac{d^2 p_{os,2}^{IDF}}{d\beta_S^2}$ as follows

$$\frac{d^2 p_{os,2}^{IDF}}{d\beta_S^2} \approx b_5 \frac{d^2 T_O}{d\beta_S^2} T_{RE} + b_3 \frac{d^2 T_O}{d\beta_S^2}. \tag{85}$$

We observe that $|b_5| > |b_3|$, $b_5 < 0$ and $T_{RE} > 1$. Hence $(b_5 T_{RE} + b_3) < 0$ and $\frac{d^2 T_O}{d\beta_S^2} < 0$. Hence, $\frac{d^2 p_{os}^{IDF}}{d\beta_S^2} \approx \frac{d^2 p_{os,2}^{IDF}}{d\beta_S^2} > 0$.

APPENDIX F

Proof of Lemma 8: To establish joint convexity of p_{os}^{IDF} with β_S and β_R, we need to show that the Hessian matrix $\mathbf{H}$ defined as follows is positive definite

$$\mathbf{H} = \begin{bmatrix} \frac{d^2 p_{os}^{IDF}}{d\beta_S^2} & \frac{d^2 p_{os}^{IDF}}{d\beta_S d\beta_R} \\ \frac{d^2 p_{os}^{IDF}}{d\beta_R d\beta_S} & \frac{d^2 p_{os}^{IDF}}{d\beta_R^2} \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix}. \tag{86}$$

In order to show $\mathbf{H}$ is positive definite, it is sufficient to show that $trace(\mathbf{H}) = \frac{d^2 p_{os}^{IDF}}{d\beta_S^2} + \frac{d^2 p_{os}^{IDF}}{d\beta_R^2} > 0$ and $\det(\mathbf{H}) > 0$. We have already established that $\frac{d^2 p_{os}^{IDF}}{d\beta_R^2} > 0$ (shown in Appendix E) and $\frac{d^2 p_{os}^{IDF}}{d\beta_S^2} > 0$, so $trace(\mathbf{H}) > 0$. We now proof $\det(\mathbf{H}) > 0$. Note that $\det(\mathbf{H}) = a_{11}a_{22} - a_{12}a_{21} = a_{11}a_{22} - a_{12}^2 > 0$, since $a_{12} = a_{21}$. We find $a_{12} = \frac{d^2 p_{os}^{IDF}}{d\beta_S d\beta_R}$ as follows

$$\frac{d^2 p_{os}^{IDF}}{d\beta_S d\beta_R} = b_1 \frac{dT_{SR}}{d\beta_S}\frac{dT_{RD}}{d\beta_R} - b_2 \frac{dT_{SD}}{d\beta_S}\frac{dT_{RD}}{d\beta_R} + b_5 \frac{dT_O}{d\beta_S}\frac{dT_{RE}}{d\beta_R}$$
$$-b_6 \frac{dT_{SE}}{d\beta_S}\frac{dT_{RE}}{d\beta_R} - b_7 \frac{dT_{SR}}{d\beta_S}\frac{dT_{RE}}{d\beta_R} - b_8 \frac{dT_{SE}}{d\beta_S}\frac{dT_{RD}}{d\beta_R} - b_9 \frac{dT_{SD}}{d\beta_S}\frac{dT_{RE}}{d\beta_R}. \tag{87}$$

We observe that $b_5, b_6 \gg b_1, b_2, b_7, b_8, b_9$. Hence, we can approximate $\frac{d^2 p_{os}^{IDF}}{d\beta_S d\beta_R}$ as

$$a_{12} = \frac{d^2 p_{os}^{IDF}}{d\beta_S d\beta_R} \approx \left(b_5 \frac{dT_O}{d\beta_S} - b_6 \frac{dT_{SE}}{d\beta_S}\right)\frac{dT_{RE}}{d\beta_R}. \tag{88}$$

Using $a_{11} = \frac{d^2 p_{os}^{IDF}}{d\beta_S^2}$ from (85) and $a_{22} = \frac{d^2 p_{os}^{IDF}}{d\beta_R^2}$ from (79), we have

$$a_{11} \approx (b_5 T_{RE} + b_3)\frac{d^2 T_O}{d\beta_S^2},\ a_{22} \approx (b_5 T_O - b_6 T_{SE})\frac{d^2 T_{RE}}{d\beta_R^2}. \tag{89}$$

Since $|b_5| \approx |b_6|$, a_{12} in (88) reduces to $a_{12} \approx |b_5|\left(\frac{dT_O}{d\beta_S} - \frac{dT_{SE}}{d\beta_S}\right)\frac{dT_{RE}}{d\beta_R}$, while a_{22} in (89) reduces to $a_{22} \approx |b_5|(T_O - T_{RE})\frac{d^2 T_{RE}}{d\beta_R^2}$. Also, $|(T_O - T_{SE})\frac{d^2 T_{RE}}{d\beta_R^2}| > |\frac{d^2 T_{RE}}{d\beta_R^2}| > |\frac{dT_{RE}}{d\beta_R}|^2$. Further $|\frac{dT_{RE}}{d\beta_R}|^2$ and $|\frac{dT_{RE}}{d\beta_R}||\frac{dT_O}{d\beta_S} - \frac{dT_{SE}}{d\beta_S}|$ are of same order, so $a_{22} > |a_{12}|$. Similarly, terms $(b_5 T_{RE} + b_3)$ and $(b_5 T_O - b_6 T_{SE})$ defined in (89) are of same order, and the dominating terms in a_{11} and a_{12} are $\frac{d^2 T_O}{d\beta_S^2}$ and $\frac{d^2 T_{RE}}{d\beta_R^2}$ respectively. Note that T_O and T_{RE} are of the form $T(x) = e^x E_1(x)$, $x \in \{\frac{\gamma_{th}}{\tilde{\Omega}\beta_S}, \frac{\gamma_{th,e}}{\tilde{\Omega}_{RE}\beta_R}\}$. Since $T(x)$ is a decreasing function of x, $T_O > T_{RE}$ since $\frac{\gamma_{th}}{\tilde{\Omega}\beta_S} < \frac{\tilde{\gamma}_{th,e}}{\tilde{\Omega}_{RE}\beta_R}$. Further, $|\frac{d^2 T_O}{d\beta_S^2}| > |\frac{d^2 T_{RE}}{d\beta_R^2}|$. Hence $a_{11} > a_{22}$. Combining this result with $a_{22} > |a_{12}|$, we get $a_{11} > a_{22} > |a_{12}|$. Therefore, $a_{11}a_{22} > a_{12}^2$ resulting in $\det(\mathbf{H}) > 0$.

APPENDIX G

Proofs of Lemmas 9: Using $\Pr(A \cap B) = \Pr(A|B)\Pr(B)$ in (45), we get

$$p_{OP}^{IDF} = \Pr\{(I_{SD} < R_t) \cap \min(I_{SR}, I_{SRD}) \le R_t\}. \tag{90}$$

Further using the identity $\Pr\{A \cap B\} = \Pr\{A\} - \Pr\{A \cap \bar{B}\}$, we get

$$p_{OP}^{IDF} = \Pr\{I_{SD} < R_t\} - \Pr\{(I_{SD} < R_t) \cap \min(I_{SR}, I_{SRD}) > R_t\}. \tag{91}$$

We then simplify (91) by substituting for I_{SR}, I_{SD} and I_{SRD} from (9), (10), and (17) respectively to get

$$p_{OP}^{IDF} = \Pr\{g_S g_{SD}\Omega_{SD} \le \gamma_{th}\}$$
$$- \Pr\{g_S g_{SD}\Omega_{SD} \le \gamma_{th}, g_S g_{SR}\Omega_{SR} > \gamma_{th}, X > \gamma_{th}\}. \tag{92}$$

Exploiting independence of g_{SR} , g_{SD} and g_{RD}, further simplifying by conditioning on g_S and g_R gives

$$p_{OP|g_S,g_R}^{IDF} = \underbrace{\Pr\{g_S g_{SD}\Omega_{SD} \le \gamma_{th}\}}_{p_{o,1|g_S}}$$
$$- \underbrace{\Pr\{g_S g_{SR}\Omega_{SR} \ge \gamma_{th}\}}_{p_{o,2|g_S}} \underbrace{\Pr\{X \ge \gamma_{th}, g_S g_{SD}\Omega_{SD} \le \gamma_{th}\}}_{p_{o,3|g_S,g_R}}. \tag{93}$$

We simplify the expressions of $p_{o,1|g_S}$ and $p_{o,2|g_S}$ as $p_{o,1|g_S} = \gamma(N, \frac{\gamma_{th}}{g_S \Omega_{SD}})$ and $p_{o,2|g_S} = e^{-\frac{\gamma_{th}}{g_S \Omega_{SR}}}$. Further $p_{o,3|g_S,g_R}$ can be simplified by also conditioning the expression over g_{SD}. Using PDF of X from (97), $p_{o,3|g_S,g_R,g_{SD}} = \int_{\gamma_{th}}^{\infty} f_X(x)dx$. Now, averaging above expression over g_{SD} in region $0 \le g_{SD} \le \frac{\gamma_{th}}{g_S \Omega_{SD}}$, we get $p_{o,3|g_S,g_R,g_{SD}}$. So, p_{OP}^{IDF} is obtained by substituting the expressions of $p_{o,1|g_S}$, $p_{o,2|g_S}$ and $p_{o,3|g_S,g_R}$ in (93). Then averaging over channels g_S and g_R we obtain (47).

APPENDIX H

Proof of Lemma 10: We substitute the information rates I_{SD} and I_{SRD} in p_{IP}^{IDF} to get

$$p_{IP}^{IDF} = \underbrace{\Pr\{g_S g_{SD} \ge \gamma_{th}/\Omega_{SD}, g_S g_{SE} > \gamma_{th}/\Omega_{SE}\}}_{p_{i,1}}$$
$$+ \underbrace{\Pr\{g_S g_{SD} < \gamma_{th}/\Omega_{SD}, Y > \gamma_{th}\}}_{p_{i,2}}. \tag{94}$$

Conditioning the expression $p_{i,1}$ on channel gain g_S, we get

$$p_{i,1|g_S} = \Pr\{g_S g_{SD} \ge \gamma_{th}/\Omega_{SD}\}\Pr\{g_S g_{SE} > \gamma_{th}/\Omega_{SE}\}$$
$$= \Gamma\left(N, \frac{\gamma_{th}}{g_S \Omega_{SD}}\right)\Gamma\left(L, \frac{\gamma_{th}}{g_S \Omega_{SE}}\right). \tag{95}$$

Using the series expansion of upper incomplete gamma function [31, 8.352.2] and averaging on the channel gain g_S and using the integral in [31, 3.471.9], we get first double summation term in (48). To simplify $p_{i,2}$, we condition the expression on channels g_S and g_R to get

$$p_{i,2|g_S,g_R} = \Pr\{g_S g_{SD} < \gamma_{th}/\Omega_{SD}\}\Pr\{Y > \gamma_{th}\}. \tag{96}$$

Similar to PDF of X, defined in (97), we can express PDF of Y by replacing N, Ω_{SD}, and Ω_{RD} by L, Ω_{SE}, and Ω_{RE} respectively in (97).

$$\begin{aligned} f_{Y|g_S,g_R}(y) &= \frac{e^{-\frac{y}{g_R\Omega_{RE}}}}{\Gamma^2(L)} \sum_{r=0}^{L-1}\binom{L-1}{r} y^r(-1)^{L-1-r}\Gamma(2L-r) \\ &\times \frac{(g_S g_R \Omega_{SE}\Omega_{RE})^{L-r-1}}{(g_R\Omega_{RE}-g_S\Omega_{SE})^{(2L-r-1)}} - \frac{e^{-\frac{y}{g_R\Omega_{RE}}}}{\Gamma^2(L)} \sum_{r=0}^{L-1}\binom{L-1}{r} \\ &\times y^r(-1)^{L-1-r}\frac{(g_S g_R \Omega_{SE}\Omega_{RE})^{L-r-1}\gamma(2L-r)}{(g_R\Omega_{RE}-g_S\Omega_{SE})^{(2L-r-1)}} \\ &\times e^{-\frac{y(g_R\Omega_{RE}-g_S\Omega_{SE})}{g_S\Omega_{SE}g_R\Omega_{RE}}} \sum_{k=0}^{2L-r-2}\frac{y^k(g_R\Omega_{RE}-g_S\Omega_{SE})^k}{(g_S\Omega_{SE}g_R\Omega_{RE})^k k!}. \end{aligned} \tag{97}$$

Therefore, first probability term in (96) will be $\Pr\{g_S g_{SD} < \gamma_{th}/\Omega_{SD}\} = \gamma(N, \gamma_{th}/\Omega_{SD})$. The second term $\Pr\{Y > \gamma_{th}\}$ is obtained as $\int_{\gamma_{th}}^{\infty} f_{Y|g_S,g_R}(y)dy$. Further averaging $p_{i,2|g_S,g_R}$ over g_S and g_R, we obtain second and third term in (48).

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