Dilemma at RF Energy Harvesting Relay: Downlink Energy Relaying or Uplink Information Transfer?

Deepak Mishra, Swades De, and Dilip Krishnaswamy

Abstract—Performance of RF powered communication network is bottlenecked by short downlink energy transfer range and doubly-near-far problem faced in uplink information transfer to Hybrid Access Point (HAP). These problems can be resolved by cooperation of an RF energy harvesting node \( R \) present between HAP and RF energy harvesting information source \( S \). However, there lies a dilemma at \( R \) on whether to transfer its harvested energy to \( S \) or to act as an information relay for transferring its data to HAP in a two-hop fashion. This paper resolves this dilemma at \( R \) by providing insights on its optimal positions suited for either energy relaying (ER) or information relaying (IR). It also investigates the possibilities of integrated ER and IR along with the regions where neither ER nor IR will be useful. In this regard, while considering Rician fading channels and practical nonlinear RF energy harvesting model, the expression for mean harvested dc power at \( S \) via energy transfer from HAP and ER from \( R \) is first derived. The closed-form outage probability expression is also derived for decode-and-forward relaying with maximal-ratio-combining at HAP over Rician channels. Using these expressions on optimal relaying mode is obtained along with global-optimal utilization of harvested energy at \( R \) for ER and IR to maximize the delay-limited RF-powered throughput. Numerical results validate the analysis and provide insights on the optimal relaying mode.

Index Terms—Integrated information and energy relaying, practical RF energy harvesting model, Rician fading, outage analysis, throughput maximization, generalized convexity

I. INTRODUCTION

Radio frequency (RF) energy transfer (ET) has drawn wide recent attention due to its capability of providing controlled energy replenishment of low-power wireless devices. Unlike the inductive and magnetic resonant coupling based non-radiative ET approaches, radiative RF-ET bestows benefits [2] like relaxed node-alignment requirements, beamforming capability, and possibility of transmitting both energy and information over the same signal. This has led to the emergence of two attractive solutions for powering next generation networks: (a) Wireless Powered Communication Network (WPCN) [3] and (b) Simultaneous Wireless Information and Power Transfer (SWIPT) [4]. In WPCN, uplink information transfer (IT) is powered by downlink ET from Hybrid Access Point (HAP), whereas in SWIPT both ET and IT occur in same direction.

Despite the merits of RF-ET, there are some bottlenecks in its widespread usage. Major challenges [5] include wireless propagation and energy dissipation losses, low energy sensitivity, low rectification efficiency at low input power, and doubly-near-far problem [6] in WPCN. Therefore, investigation of new paradigms is needed for efficient WPCN operation.

A. Related Art

Various aspects of cooperative relaying have got recent research attention [5]–[20] to overcome doubly-near-far problem [21] in WPCN and large difference between energy and information sensitivities (−10 dBm versus −60 dBm) in SWIPT. The authors in [5]–[10], [16]–[20] considered energy harvesting relay where an energy constrained node uses the harvested energy for cooperation. Optimal RF harvesting energy relay placement was investigated in [5] for maximizing the received power in two-hop RF-ET, both with and without distributed beamforming. In [6], a nearby node to HAP was considered to act as energy harvesting information relay for the farther node. A harvest-then-cooperate protocol was proposed in [7], where the relay node close to HAP harvests energy during downlink ET from HAP and then uses this energy for uplink information relaying (IR). The authors in [19] investigated instantaneous and delay-constrained throughput maximization for RF-powered full-duplex MIMO relay system by designing receive and transmit beamformers while optimizing the time-splitting parameter. A three-node RF-powered relay system was studied in [20] to maximize the ergodic throughput by optimizing the mode switching rule and transmit power jointly under the data and energy causality constraints.

Different from [6], [7] which considered fixed relaying, the approach in [8] dynamically decides whether the nearby node should act like an information relay for far node or not. Further in [9], the roles as source, destination, or relay, for the nodes were dynamically decided. Optimal allocation of harvested energy at relay, due to SWIPT from multiple sources for forwarding data to their respective receivers, was considered in [10]. In [16] a greedy protocol was proposed for switching between energy harvesting and data relaying to minimize outage probability in amplify-and-forward (AF) energy harvesting relay network without direct link. In [17] this work was extended to distributed multi-relay selection with decode-and-forward (DF) two-hop IT. More recently, a relay selection scheme, incorporating channel conditions and battery status, was proposed in [18] to choose one among multiple AF energy harvesting relays for IT. Furthermore, energy cooperation and sharing strategies have been proposed in [11], [12] to overcome dynamics of ambient energy harvesting and enable perpetual operation. In another set of works [13]–[15],
relay-powered communications was considered, where energy-sufficient relay transfers energy to RF harvesting nodes.

B. Motivation and Contributions

In recent studies, harvested energy at relay is either used for energy relaying (ER) [5] or IR [6]–[10], [16]–[20]. Though [13]–[15] studied tradeoff in ET and IR efficiency assuming energy-rich relay, these works along with [11], [12] did not investigate RF harvesting relay assisted ER possibilities. This work fills this existing research gap. It studies optimal utilization of harvested energy at RF-energy harvesting (EH) relay for ER and/or IR to enhance the performance of two-hop RF-powered delay-limited network with direct link availability. Key contributions of this work are six-fold: (1) As shown in Fig. 1, a novel system model is presented to investigate the performance of RF-powered integrated information and Energy Relaying (i^2ER) in WPCN (Section II). (2) Mean harvested energy due to full-duplex ER over Rician fading channels with distributed beamforming is derived while considering practical RF harvesting model (Sections III). (3) Closed-form expressions for outage probability and normalized throughput are obtained for half-duplex DF-IR over Rician channels with Maximal Ratio Combining (MRC) (Section IV). (4) Analytical insights on optimal mode selection policy at RF harvesting relay are provided (Section V). (5) Global-optimal utilization of harvested energy at EH relay is obtained by efficiently solving the nonconvex delay-limited throughput maximization problem (Section VI). (6) Numerical results validate the analysis and give insights on optimal harvested energy utilization in ER and IR for varying relay positions (Section VII).

C. Novelty and Scope

To the best of our knowledge, this is the first work that considers i^2ER in WPCN and resolves the “dilemma” at RF harvesting relay on whether to perform ER, IR, or i^2ER by jointly optimizing cooperation in ET and IT. We also present novel analyses on full-duplex ER with distributed beamforming and half-duplex DF-IR with MRC over Rician channels.

Results presented in this paper demonstrate the importance of i^2ER, because in static node deployment scenarios where the relay position is fixed or the set of available routers are known, mode selection (ER or IR) becomes critical. This work providing insights on optimized mode of cooperation with RF harvesting relay (for energy, information, or both) can be extended to multi-node scenarios, allowing IR on one path and ER on other for greater end-to-end efficiency depending on the position of the relays. Energy beamforming [3] can also be applied over the proposed optimized cooperation for further enhancement of achievable gains. Though the widespread utility of the proposed system architecture is constrained by the low RF-ET range [2], [5], there are some practical applications that can benefit from this proposal. These include low power EH nodes in small cell networks, miniature RF-powered sensing devices for indoor applications, and EH nodes in Internet-of-Things. Furthermore, with the advancement in RF-EH circuits technology [22], [23], this limited end-to-end RF-ET range will be significantly increased due to improvement in both RF-to-dc rectification efficiency and receive energy sensitivity. Another attractive solution to improve the performance of the proposed RF-powered i^2ER is by implementing the full-duplex IR. However this improvement comes at the expense of implementing loopback interference suppression with the help of sophisticated electronic schemes or spatial domain precoding techniques that require perfect channel estimation. So there is a need for low-cost energy-efficient full-duplex IR techniques for RF-powered relaying systems.

II. SYSTEM MODEL

Here we present the i^2ER system model that includes transmission protocol, network topology, and wireless channel, along with the energy consumption and RF harvesting models.

A. Integrated Information and Energy Relaying in WPCN

We consider RF-EH relay \( R \) assisted full-duplex two-hop downlink ET to RF-EH information source \( S \) and DF half-duplex uplink IT to HAP \( A \) (cf. Fig. 1). We assume that \( A \) and \( S \) are composed of single omnidirectional antennas, whereas \( R \) has two directional antennas; one pointing in the direction of \( A \) – essentially for efficient EH at \( R \) and effective IR from \( R \)-to-\( A \), and other directed towards \( S \) for efficient downlink ER and improving the quality of \( S \)-to-\( R \) uplink IT. Although half-duplex IR can be conducted using a single omnidirectional antenna at \( R \), two directional antennas are considered to minimize the dissipation losses in downlink ER and uplink IR. Also, this helps in implementing two-hop full-duplex ER because RF energy signals do not contain any information to be lost during full-duplex operation. The role of full-duplex relaying in ER phase is to ensure that \( R \) can simultaneously harvest energy from \( A \) as well transfer energy to \( S \) in the \( N_s \)th slot. Moreover, as the dimensions of the directional and omnidirectional antennas are similar [24] and the storage capacity of commercially available efficient compact supercapacitors [25] is large enough to store the harvested energy over multiple slots \( N_s \), the form factor and storage capability are not a concern in the proposed i^2ER architecture. The entire i^2ER process can be divided into three phases, as highlighted in Fig. 1 and Table I:

1. **RF-ET over \( N_s \) slots:** Apart form single-hop ET from \( A \) to \( R \) and \( S \) over \( N_s \) slots, last or \( (N_s) \)th slot of this phase
TABLE I: Description of operations in RF-powered communication with energy and information relaying possibility.

<table>
<thead>
<tr>
<th>Duration</th>
<th>Slots #</th>
<th>Information Transfer</th>
<th>RF Energy Transfer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ns, slots</td>
<td>1 slot</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Ns+1 slots</td>
<td>1 slot</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Ns+2 slots</td>
<td>1 slot</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

also involves two-hop full-duplex ET from R to S using \( \beta \alpha \) fraction of energy harvested \( E_{hR} \) at R over \( N_s \) slots.

(2) **IT from S to A and R** during \((N_s + 1)\)th slot using its energy harvested over \( N_s \) slots.

(3) **IT from R to A** in \((N_s + 2)\)th slot using \( \beta (1 - \alpha) \) fraction of harvested energy \( E_{hR} \) at R.

Following the summary given in Table I, we note that all four possible relaying modes are: no relaying (NR), ER, IR, and i^2ER. In NR (i.e., neither ER nor IR) mode, indicator variable \( \beta \) is set to zero, \( \beta = 1 \) for other modes represents that R uses \( \alpha \) fraction of its harvested energy \( E_{hR} \) for ER and remaining fraction for IR. Thus \( \alpha = 1 \) and \( \alpha = 0 \) respectively represent ER and IR scenarios, whereas \( 0 < \alpha < 1 \) represents the i^2ER mode. Here it is worth noting that, since the energy harvested over a single slot is very low (as shown later in Fig. 3), we have considered \( N_s > 1 \) slots for RF-ET because it helps in incorporating the hardware limitations of RF-EH communication [2], [5] while giving insights on the practically realizable rate-constrained sustainable throughput performance (cf. Section VII). Also, in order to have sufficient harvested energy at R for efficient RF-ET to S, ER is considered only in the \( N_s \)th slot. Further, due to the usage of two directional antennas at R, the leaked energy from R in the unintended direction, that could be recycled by its receiver, is neglected.

**B. Network Topology**

To avoid blocking of direct ET and IT paths between A and S, we consider parallel topology [5] for relay placement. Considering static node deployment, A and S are respectively located on Euclidean plane with coordinates \((0, 0)\) and \((d_{AS}, 0)\). Here \( d_{AS} \) is the distance between A and S. R is positioned at \((x_R, y_{R0})\), where \( y_{R0} \) is the minimum non-blocking distance [5] from Line-of-Sight (LoS) path between A and S. However, it is worth mentioning that the proposed i^2ER model and the analysis hold for any arbitrary relay placement topology ensuring the availability of unaffected direct link between A and S, e.g., elliptical topology [13].

**C. Channel Model**

All the links are considered independent and experience flat quasi-static Ricean block fading [13], where the average channel power gains \( |h_{ij}|^2 = E[|h_{ij}|^2] = \frac{G_i G_j}{d_{ij}^\lambda} \left( \frac{\lambda}{4\pi} \right)^2 \), \( \forall i, j \in \{A, R, S\} \) Here \( G_i \) and \( G_j \) represent antenna gain for transmitting node i and receiving node j; \( \lambda \) is the wavelength of transmitted RF signal; \( n \) is path loss exponent; \( d_{ij} \) corresponds to distance between nodes i and j. Rician channel model helps in incorporating the effect of strong LoS component in RF-ET over short range IT links. Rician fading also includes Rayleigh fading [6]–[10] as its special case. To reduce signalling overhead at energy-constrained R and S, we assume that knowledge about statistics of channel state information (CSI), instead of instantaneous CSI, for all links is available at A via pilot signals received from R and S.

**D. Energy Consumption and RF Relaying Model**

We assume that \( S \) uses its entire harvested energy for IT. So with unit slot duration \( T = 1 \) s, energy or power consumption at \( S \) during IT is: \( P_{ts} + P_{\text{con}}^S \), where \( P_{\text{con}}^S \) is static power consumption independent of transmit power \( P_{ts} \). Generally \( P_{\text{con}}^S \approx 0 \) in cooperative WPCN and SWIPT [6]–[10]. We note that RF energy reception does not consume any power [2], [5]. The consumption at R for IR is accounted as [26, Table I]: \( E_{\text{con}}^R + R_0 E_{\text{bit}}^R \), where \( E_{\text{con}}^R \) is static consumption and \( R_0 E_{\text{bit}}^R \) is consumption in reception and decoding of \( R_0 \) bits.

The harvested dc power \( P_h \) is a nonlinear function of received RF power \( P_r \) [5]. To this end, we present a piecewise linear approximation for establishing a relationship between \( P_h \) and \( P_r \) using a piecewise linear function \( \mathcal{L}(\cdot) \). Mathematically, \( \mathcal{P}_h = \mathcal{L}(\mathcal{P}_r) \) can be defined as:

\[
\mathcal{P}_h = \begin{cases} 
0, & \mathcal{P}_r < \mathcal{P}_{th_1}, \\
M_i \mathcal{P}_r + C_i, & \mathcal{P}_{th_i} < \mathcal{P}_r < \mathcal{P}_{th_{i+1}}, \forall i = 1, \ldots, N, \\
\text{Not applicable,} & \mathcal{P}_{th_{N+1}} < \mathcal{P}_r.
\end{cases}
\]

where \( \mathcal{P}_{th_i} = \{\mathcal{P}_{th_0} \mid 1 \leq i \leq N+1\} \) mW are thresholds on \( \mathcal{P}_r \) that define the boundaries for \( N \) linear pieces with slope \( M_i = \{M_i \mid 1 \leq i \leq N\} \) and intercept \( C = \{C_i \mid 1 \leq i \leq N\} \) mW.

We have used the above approximation \( \mathcal{L}(\cdot) \) because this simple linear relationship between \( \mathcal{P}_r \) and \( \mathcal{P}_h \) helps in gaining insights on global-optimal harvested energy utilization and proving conditional-unimodality of throughput maximization problem (P1) in \( \alpha \) (cf. Section VI).

**III. DOWNLINK RF ENERGY TRANSFER AND ENERGY RELAYING OVER RICIAN CHANNELS**

The energy signals \( \gamma_{\lambda R} \) and \( \gamma_{\lambda A} \) received respectively at R and S in one slot of ET from A are given by:

\[
\gamma_{\lambda \mathcal{N}} = X_{\lambda A} \sqrt{P_{\lambda A}^R} |h_{\lambda \mathcal{N}}| e^{-j \Theta_{\lambda \mathcal{N}}} + \eta_{\lambda \mathcal{N}}, \forall \mathcal{N} = \{R, S\},
\]

where \( X_{\lambda A} \) is the zero mean and unit variance energy signal transmitted by A, and \( P_{\lambda A}^R \) is the transmit power of A. \( |h_{\lambda \mathcal{N}}| \) and \( \Theta_{\lambda \mathcal{N}} = \frac{2\pi d_{\lambda \mathcal{N}}}{\lambda} - \phi_{\lambda \mathcal{N}} \) respectively represent the amplitude and phase of the Ricean channel fading coefficient for the link between node i and node j, where \( i,j = \{A,R,S\} \). Here \( \frac{2\pi d_{\lambda \mathcal{N}}}{\lambda} \) represents the phase difference due to free space path delay and \( \phi_{\lambda \mathcal{N}} \) represents the sum of all other phases that include phase weights introduced for synchronization, errors due to the local oscillator variations, excess path phase from obstacles, etc. [27]. Lastly, \( \eta_{\lambda \mathcal{N}} \) represents zero mean additive white Gaussian noise with variance \( \sigma^2 \) as received at node i.
Using (2) and ignoring EH from noise power [6]–[15], the received power at \( R \) and \( S \) in each slot due to RF-ET from \( A \) is given by (3) where \(^\dagger\) denotes the complex conjugate.

\[
P_{rAN} = \left| (Y_{rAN}) (Y_{sAN}) \right|^2 = P_A |h_{AN}|^2, \quad \forall N = \{ R, S \}. \tag{3}
\]

As the received powers \( P_{rAS} \) and \( P_{rAR} \) at \( R \) and \( S \) involve the square of Rician distributed \(|h_{AN}|\), they follow noncentral-\( \chi^2 \) distribution with respective Rice factors and means as 
\[
K_{AS}, \mu_{rAS} = \frac{P_A G_A(G_S)}{(d_{AS})^2} \left( \frac{\lambda}{4\pi} \right)^2
\]

\[
K_{AR}, \mu_{rAR} = \frac{P_A G_A G_R}{(d_{AR})^2} \left( \frac{\lambda}{4\pi} \right)^2.
\]

We next discuss the basic probabilistic measures for the received power over Rician channels and then use them for deriving the mean harvested energy at \( S \) due to RF-ET from \( A \), both with and without ER.

### A. Basic Properties of Rician Fading Channels

For Rician fading, the channel power gains follow noncentral-\( \chi^2 \) distribution with two degrees of freedom. Thus, the probability density function (PDF) \( f_{P_r} \) of received power \( P_r, \forall x \geq 0 \), is given by:

\[
f_{P_r}(x, K, \mu_p) = \frac{e^{-\frac{(K+1)x}{\mu_p}} - K}{\mu_p(K+1)^{-1}} I_0 \left( 2 \sqrt{\frac{K(K+1)x}{\mu_p}} \right), \tag{4}
\]

where \( K \) is Rice factor, \( \mu_p \) is mean received power, and \( I_0(\cdot) \) is the modified Bessel function of the first kind with order \( m \).

The Cumulative Distribution Function (CDF) \( F_{P_r} \) of \( P_r \) is:

\[
F_{P_r}(x, K, \mu_p) = 1 - Q_1 \left( \sqrt{2K} \sqrt{2(K+1)x/\mu_p} \right), \tag{5}
\]

where \( Q_1(\cdot) \) is first order Marcum Q-function [28].

Moment generating function (MGF) \( \Phi_{P_r}(\nu, K, \mu_p) \) of \( P_r \) can be obtained as:

\[
\Phi_{P_r}(\nu, K, \mu_p) = \begin{cases} 
\frac{K+1}{K-\nu/\mu_p+1} e^{\frac{\nu}{\mu_p} - \nu/\mu_p - 1} & \nu < \mu_p - K \\
\frac{K+1}{K-\nu/\mu_p+1} e^{\frac{\nu}{\mu_p} + \nu/\mu_p - 1} & \nu > \mu_p - K.
\end{cases} \tag{6}
\]

Here (a) is obtained by using [29, eq. (2.17)] and (b) is obtained after a rearrangement in (a).

### B. Single-Hop RF-ET from \( A \) to \( S \) and \( R \)

First we obtain mean harvested power \( \overline{P}_{hAS} \) at \( S \) and \( \overline{P}_{hAR} \) at \( R \) in each slot dedicated for RF-ET from \( A \). Using \( P_h = \mathcal{L}(P_r) \) as defined in (4) along with PDF \( f_{P_r} \) and CDF \( F_{P_r} \) of received power \( P_r \) defined in (4) and (5), the PDF \( f_{P_h} \) of harvested dc power \( P_h \) is obtained as:

\[
f_{P_h}(x, K, \mu_p) \triangleq \frac{1}{M_f} f_{P_r} \left( \frac{x-C_j}{M_f}, K, \mu_p \right) \frac{1}{F_{P_r}(P_{h_{b+1}}) - F_{P_r}(P_{h_b})}, \tag{7}
\]

where \( x \) satisfies \( P_{h_b} \leq \frac{x-C_j}{M_f} \leq P_{h_{b+1}}, \forall j \in 1, \ldots, N \). Thus, using (7), the mean harvested dc powers \( \overline{P}_{hAN} \) where \( N = \{ R, S \} \) are derived below:

\[
\overline{P}_{hAN} = \mathbb{E}[P_{h_{AN}}] = \int_0^\infty f_{P_{h_{AN}}} \left( x, K_{AN}, \mu_{P_{AN}} \right) \, dx
\]

\[
= \sum_{j=1}^N \frac{M_f P_{b_{b+1}} + C_j}{M_f} \frac{(K_{AN} + 1) e^{(K_{AN} + 1)(x-C_j)} - K_{AN}}{M_f P_{AN}} \int_0^\infty 2 \sqrt{\frac{K_{AN}(K_{AN} + 1)(x-C_j)}{M_f P_{AN}}} e^{\frac{\nu}{\mu_p} - \nu/\mu_p - 1} \, d\nu
\]

\[
= \sum_{k=0}^\infty \sum_{j=1}^N \frac{M_f P_{b_{b+1}} + C_j}{M_f} \frac{(K_{AN} + 1) |K_{AN}| |K_{AN} + 1| x e^{-K_{AN} - K_{AN} + 1}}{M_f P_{AN}} \int_0^\infty 2 \sqrt{\frac{K_{AN}(K_{AN} + 1)(x-C_j)}{M_f P_{AN}}} e^{\frac{\nu}{\mu_p} - \nu/\mu_p - 1} \, d\nu
\]

\[
= \sum_{k=0}^\infty \sum_{j=1}^N e^{-K_{AN} (K_{AN} + 1)} e^{\frac{\nu}{\mu_p} - \nu/\mu_p - 1} \, d\nu
\]

\[
\text{where } g_{N,j}(P_{b_{b+1}}) \triangleq C_j (K_{AN} + 1) \Gamma \left( k + 1, \frac{(K_{AN} + 1) P_{b_{b+1}}}{\mu_{P_{AN}}} \right) + M_f \mu_{P_{AN}} \Gamma \left( k + 2, \frac{(K_{AN} + 1) P_{b_{b+1}}}{\mu_{P_{AN}}} \right).
\]

Each term in Taylor series expansion of \( I_0(\cdot) \) used in (c) can be upper bounded as:

\[
\left( \frac{(K_{AN} + 1)}{(K_{AN} + 1)} \right)^k \approx \left( \frac{4 K_{AN} (K_{AN} + 1)}{(K_{AN} + 1)} \right)^k \]

\[
\leq \left( \frac{2 \pi (K_{AN} + 1)}{k} \right)^{2k}.
\]

Here (d) is obtained by knowing that generally \( (x - C_j) \leq 4 M_f P_{b_{b+1}} \), as from (5) \( P_r > 4 \mu_p \) < 0.009, \( K > 1 \), and (e) is obtained using the Stirling’s approximation [30]: \( j! \approx \sqrt{2\pi e^{-j} j^{j+\frac{1}{2}}} \). From (9) we note that the contribution of higher order terms \( k > \ln \left( \frac{1}{2} \right) \) is very less than \( \epsilon \) where \( \epsilon \ll 1 \) and \( W_0(x) \) is the Lambert function (principal branch) [31]. However, in general for high Rice factor \( K_{AN} \geq 10 \), even considering only first \( k = e (K_{AN} + 1) \) summands provides a very tight match to the infinite series because the product term \( \frac{\nu}{\mu_p} - \nu/\mu_p - 1 \) decays very fast with increasing \( K_{AN} \). This has been numerically validated later in Fig. 3 where (8) is shown to be equivalent to the sum of first 30 summands.

So, with \( T = 1 \) s as slot duration, mean harvested energy \( E_{h_{b+1}} \) at \( R \) via RF-ET from \( A \) over \( N_s \) slots is: \( E_{h_{b+1}} \triangleq \overline{P}_{h_{AR}} N_s \). Similarly for NR and IR (i.e., no ER modes), the mean harvested energy at \( S \) is: \( E_{h_{b+1}} \triangleq \overline{P}_{h_{AS}} N_s \). However for ER and iER modes, mean harvested energy at \( S \) via single hop ET from \( A \) over \( N_s - 1 \) slots is: \( E_{h_{b+1}} \triangleq \overline{P}_{h_{AS}} (N_s - 1) \). Next we find energy harvested at \( S \), via two-hop ET from \( R \), in the last slot of RF-ET phase in ER and iER modes.

### C. Mean Energy Harvested in \( N_s \)th Slot due to Two-Hop ER

The received energy signal \( Y_{RS} \) at \( S \) in the \( N_s \)th slot due to ER from \( R \) is given by:

\[
Y_{RS} = X_{ER} \sqrt{3 \alpha P_{rS}} |h_{RS}| e^{-i\Theta_{RS}} + N_s, \tag{10}
\]
where $X_{R_s}$ is the zero mean, unit variance energy signal transmitted by $R$ using its energy harvested $E_{h_R}$ over $N_s$ slots and $P_{tr}$ is the transmit power of $R$. $\beta$ is indicator variable for relaying with $\alpha$ as fraction of $E_{h_R}$ allocated for ER. $\Theta_{R_s}$ and $\psi_{R_s}$ are $(2\pi N_s - \phi_{R_s})$ respectively represent the amplitude and phase of Rician fading coefficient for $R$-to-$S$ link. So, we note that if ER takes place from $R$ to $S$, i.e., $\alpha > 0$, then $S$ receives two energy signals $Y_{AS}$ and $Y_{RS}$ in the $N_s$th slot and the received power at $S$ in the $N_s$th slot is different from (3). Thus using (3) and (10), the random received power $P_{rs}^{\text{hop}}$ at $S$ in $(N_s+1)$th slot of ER phase, due to vector addition of energy signals received from $A$ and $R$, is given by [5, eq. (14)]:

$$P_{rs}^{\text{hop}} = \left[ (Y_{AS} + Y_{RS}) (Y_{AS} + Y_{RS}) \right] = Y_{AS}^2 + Y_{RS}^2 + 2|Y_{AS}||Y_{RS}|e^{-j(\Theta_{AS} - \Theta_{RS})} + \beta_0 P_{R_{AS}} + 2 \sqrt{P_{R_{AS}}/\beta_0} e^{-j\psi_{RS}} \left( 2\pi (d_{AS} - d_{RS}) \right),$$

(11)

where $\overline{\psi^2}$ is the root mean square phase error term incorporating the errors due to the local oscillator variations, excess path phase from obstacles, etc. $\overline{\psi^2}$ is in radians and $e^{-j\psi}$ is unit-less. Here vector addition of RF signals of same frequency received from $A$ and $R$ is considered because these energy waves can combine constructive or destructively depending on their respective in-phase or out-of-phase addition [5]. So, mean received power $P_{rs}^{\text{hop}} = E\left[P_{rs}^{\text{hop}}\right]$, obtained using linearity of expectation and independence of $P_{R_{AS}}$ and $P_{R_{RS}}$, is:

$$P_{rs}^{\text{hop}} = E[P_{R_{AS}}] + \beta_0 E[P_{R_{RS}}] + 2 \beta_0 E\left[\sqrt{P_{R_{RS}}}\right] \times \left[ \sqrt{P_{R_{RS}}} e^{-j\psi} \left( 2\pi (d_{AS} - d_{RS}) \right) = \mu_{R_{AS}} + \beta_0 \mu_{R_{RS}} + 2 \beta_0 \mu_{R_{RS}} e^{-j\psi} \right),$$

(12)

where $\mu_{R_{AS}} = \frac{E_{R_s} + E_{h_R} G_{AS} G_S}{(d_{AS})^{\lambda}} \left( \frac{\lambda}{\pi} \right)^2$ and $E_{h_R}$ as defined in Section III-B. Here $E_{h_R}$ is the unused harvested energy which is available as the residual or initial energy at $R$ when NR mode was selected in the previous transmission block. The accumulated energy $E_{h_R}$ is zero when any other relaying mode is chosen. $\mu_{R_{RS}}$ and $\mu_{R_{RS}}$ in (12) are respectively obtained by substituting $\mu_{R_{AS}}$ and $\mu_{R_{RS}}$ in place of $\mu_\sigma$ in (13) providing $E\left[\sqrt{P_{R_s}}\right]$.

$$\mu_{\sqrt{P_{R_s}}} = e^{-\frac{K}{2}} \sqrt{\frac{2\mu_{R_{AS}}}{\lambda}} \left( K + 1 \right) I_0 \left( \frac{K}{2} \right) + K I_1 \left( \frac{K}{2} \right).$$

(13)

The above expression is obtained by finding the mean of square-root of random variable $P_{R_s}$ following noncentral-$\chi^2$ distribution with two degrees of freedom.

Using (12) and (13), the mean harvested power at $S$ due to ER in last slot of RF-ET phase is given by $P_{\text{hop}}^{E_{RS}} = E_{h_{RS}} + P_{\text{hop}}^{\text{hop}}$. The total energy harvested at $S$ in $N_s$ slots for ER and i$^2$ER modes is: $E_{h_{RS}} = E_{h_{RS}}^{N_s-1} + P_{\text{hop}}^{\text{hop}}$. For NR and IR, $P_{\text{hop}}^{\text{hop}} = P_{h_{AS}}$, which implies that $E_{h_{RS}} = P_{h_{RS}}N_s$.

**IV. DF RELAY ASSISTED COMMUNICATION OVER RICIAN CHANNELS WITH DIRECT LINK**

For the RF-powered IT with $T = 1$ s, the transmit powers $P_{tr} = E_{h_{RS}} + E_{12}$ and $P_{ts} = E_{h_{RS}}$ of $R$ and $S$ depend on their usable harvested energies $E_{h_{RS}} = \beta_0 \left( 1 - \alpha \right) P_{h_{AS}} N_s - P_{\text{con}} - E_{\text{con}} - R_0 E_{\text{con}}$ and $E_{h_{RS}} = \left[ P_{h_{RS}} - P_{\text{con}} \right]^+$ for IT, as discussed in Sections II-D and III. Here $[x]^+ = \max \{0, x\}$. With $P_{ts}$ as transmit power of $S$ and $X_{is}$ as zero mean and unit variance information signal, the received signals at $R$ and $A$ due to uplink IT from $S$ in $(N_s + 1)$th are:

$$Y_{RS} = X_{is} \left( P_{is} \right) h_{RS} \left| e^{-j\Theta_{RS}} \right. + \tilde{N}_R, \forall N = \{A, R\}.$$  

(14)

From the received information symbol $Y_{RS}^2$, $R$ forwards the decoded zero mean, unit power signal $X_{is}$ to $A$ using its harvested energy with transmit power $P_{ts}$ in a two-hop half-duplex fashion in the $(N_s + 2)$th slot. The RF signal, thus received at $A$ is given by:

$$Y_{RA} = X_{is} \left( P_{is} \right) h_{RA} \left| e^{-j\Theta_{RA}} \right. + \tilde{N}_A.$$  

(15)

For Rician fading channel model, the instantaneous signal-to-noise ratio (SNR) $\gamma = \frac{P_{is}}{\sigma^2}$ follows the weighted noncentral-$\chi^2$ distribution with two degrees of freedom. Using (14) and (15), the received SNRs $\gamma_{SR}, \gamma_{RA},$ and $\gamma_{SA}$ of $S$-to-$R, R$-to-$A, S$-to-$A$ links, respectively, are given by:

$$\gamma_{R_{12}} = \frac{P_{R_{12}} \gamma_{R_{12}}}{\sigma^2} = \frac{1}{\sigma^2} \left( h_{R_{12}} \right)^2,$$

(16)

$\forall (N_1, N_2) = \{S, R\}, \{R, A\}, \{S, A\}$. Due to the availability of the direct link and MRC of received signals at $A$, the received SNR at $A$ involves the sum of $\gamma_{SR}$ and $\gamma_{RA}$. Next we derive the distribution of this sum to obtain the closed-form expressions for outage probability and normalized throughput at $A$ due to IT from $S$ using harvested energy.

**A. Sum of Two Weighted Noncentral-$\chi^2$ Random Variables**

The distribution of sum of two positive weighted noncentral-$\chi^2$ random variables can be obtained in terms of Laguerre expansions [32, eq. (3.5)]. However, due to the involvement of complicated recursions in PDF and CDF expressions, its usage has been limited and an integral definition was used in [13]. Here, we present simple expressions for PDF and CDF of this sum by using series expansion of exponential function. The PDF $f_{\gamma_{S_1} + \gamma_{S_2}}(x)$ of sum of two positive weighted noncentral-$\chi^2$ random variables $\gamma_{S_1}$ and $\gamma_{S_2}$ having respective Rice factor and mean as $(K_1, \mu_{\gamma_1})$ and $(K_2, \mu_{\gamma_2})$ is given by:

$$f_{\gamma_{S_1} + \gamma_{S_2}}(x, K_1, \mu_{\gamma_1}, K_2, \mu_{\gamma_2}) = \frac{1}{2\pi} \int_{-\infty}^{\infty} e^{-\nu x} \Phi_{\gamma_{S_1}}(\nu, K_1, \mu_{\gamma_1}) \Phi_{\gamma_{S_2}}(\nu, K_2, \mu_{\gamma_2}) d\nu.$$  

(17)

$$= \frac{1}{2\pi} \int_{-\infty}^{\infty} \sum_{j=0}^{\infty} \sum_{k=0}^{\infty} \left( \frac{K_1(K_1+1)}{K_1-k \mu_{\gamma_1}+1} \right)^j \left( \frac{K_2(K_2+1)}{K_2-k \mu_{\gamma_2}+1} \right)^{j+1} \nu^{j+k+1} d\nu.$$  

(18)

$$= \sum_{j=0}^{\infty} \sum_{k=0}^{\infty} \left( \frac{K_1(K_1+1)}{\mu_{\gamma_1}} \right)^j \left( \frac{K_2(K_2+1)}{\mu_{\gamma_2}} \right)^{j+1} \nu^{j+k+1}.$$  

(19)
\[
\Gamma (a, x) = \int_x^\infty t^{a-1} e^{-t} \, dt \quad \text{is upper incomplete gamma function. As with } a = j + 1 < j + k + 2 = b, (a)_b x^a \leq z^b, \text{ we note that } j^* \text{ for the Lagrange remainder } R_l^j \text{ in the Taylor series expansion of } F_1(a; b; x) \text{ to be less than } c, \text{ is lesser than in case of Lagrange remainder in the Taylor series expansion of exponential function } e(x). \text{ Hence, although (20) involves three series, each of the three infinite sum-terms converge very quickly. Also we show later in Fig. 4 that practically this CDF reduces to a finite sum with only 30 summands in each series.}
\]

Similarly using (19), the expression for CDF of \( P_{\rho_1 + P_{\rho_2}} \) for Rayleigh fading channels is:

\[
P_{\rho_1 + P_{\rho_2}} (x; \mu_{\rho_1}, \mu_{\rho_2}) = 1 - \mu_{\rho_1} e^{-\frac{x}{\mu_{\rho_1}}} - \mu_{\rho_2} e^{-\frac{x}{\mu_{\rho_2}}}. \tag{21}
\]

Using (19) and (21), the \( i^2 \) ER performance over Rayleigh fading channels can be investigated.

### B. Outage Analysis for RF-powered DF-IR with MRC

The outage probability \( p_{out} \) is the probability that the data rate received at \( A \) during IT (and IR) phase (of duration 1 or 2 slots depending on relaying mode) falls below a spectral efficiency threshold \( R_0 \) bits/sec/Hz or bps/Hz. Considering half-duplex DF-IT from \( S \) to \( A \) via \( R \) with MRC at \( A \) due to direct link availability, the outage probability \( p_{out}^R \) for IR or \( i^2 \) ER over the Rician channels is given by:

\[
p_{out}^R \overset{(i)}{=} \Pr \left\{ \frac{1}{2} \log_2 \left( 1 + \min \{\gamma_{SR}, \gamma_{RA} + \gamma_{SA}\} \right) < R_0 \right\} = \Pr \left\{ \min \{\gamma_{SR}, \gamma_{RA} + \gamma_{SA}\} < 2R_0 - 1 \right\} = 1 - \Pr \left\{ \gamma_{SR} > 2R_0 - 1 \right\} \Pr \left\{ \gamma_{RA} + \gamma_{SA} > 2R_0 - 1 \right\}
\]

\[
=p_{out}^R \overset{(ii)}{=} 1 - \left[ 1 - F_{P_{SR}} \left( 2R_0 - 1; \frac{K_{SR}}{\sigma^2_{PSR}}, \frac{\mu_{PSR}}{\sigma^2_{PSR}} \right) \right] - F_{P_{RA} + P_{SA}} \left( 2R_0 - 1; \frac{K_{RA}}{\sigma^2_{PSA}}, \frac{\mu_{PSA}}{\sigma^2_{PSA}} \right) - F_{P_{RA} + P_{SA}} \left( 2R_0 - 1; \frac{K_{SA}}{\sigma^2_{PSA}}, \frac{\mu_{PSA}}{\sigma^2_{PSA}} \right), \tag{22}
\]

where \( (i) \) is due to half-duplex DF-IR with MRC [13], \( (ii) \) is obtained using (16) and fact that \( \gamma_{N_1, N_2} \) follows noncentral-\( \chi^2 \) distribution with two degrees of freedom, Rice factor \( K_{N_1, N_2} \), and mean number of paths \( \mu_{P_{N_1, N_2}} \) defined as:

\[
\frac{\mu_{P_{N_1, N_2}}}{\sigma^2_{PSR}} = \left( \frac{g_{N_1}}{g_{N_2}} \right)^2 \left( \frac{\sigma_{PSR}}{\sigma^2_{PSR}} \right)^2, \forall \left( N_1, N_2 \right) = \{(S, R), (R, A), (S, A)\}. \]
C. Achievable Normalized Throughput in RF-powered $i^2$ER

Normalized throughput $\tau$ is the amount of successfully transmitted data per unit time in each communication slot. Considering a delay-limited scenario with rate constraint (outage threshold) of $R_0$ bps/Hz at $A$ for IT phase of 1 or 2 slots (Table I), $\tau$ for different relaying modes is:

$$\tau \triangleq \begin{cases} 
R_0(1-p_{\text{out}})N_s, & \text{NR (}\beta = 0\text{) and ER (}\beta = \alpha = 1) \\
\frac{R_0(1-p_{\text{out}})}{2R_0(1-p_{\text{out}})}(\alpha+1), & \text{IR (}\beta = 1, \alpha = 0) \text{ and } i^2\text{ER (}\beta = 1\). 
\end{cases}$$ (25)

V. Optimal Mode Selection at RF-EH Relay

We now discuss the insights on which mode to choose among NR, ER, IR, and $i^2$ER. This optimal mode selection policy for efficient outage performance basically involves two main decision making: (i) Two-hop IT with IR or single-hop IT without IR (Section V-B), and (ii) RF-powered S-to-A IT with ER or without ER (Section V-A). Fig. 2 summarizes the decision making process in the optimal relaying mode selection policy. Subsequently, we derive conditions for the improved performance of cooperative ER, IR, and $i^2$ER modes over non-cooperative NR mode.

A. Feasibility of Energy Relaying (ER) Mode

First we derive conditions for improved performance of ER over NR. ER mode is useful when the transmit power $P_{IS}$ of $S$, based on its harvested energy $E_{h_{S}}^{\text{ER}}$ from $A$ and $R$ jointly, is more than the harvested energy $E_{h_{S}}^{\text{NR}}$ from $A$ alone, i.e., without ER. Knowing $E_{h_{S}}^{\text{ER}} = P_{h_{AS}} N_s$ and $P_{h_{AS}} \approx \mathcal{L}(\mu_{P_{AS}})E_{h_{S}}^{\text{NR}}$ defined in Section III-C can be rewritten as:

$$E_{h_{S}}^{\text{ER}} = E_{h_{S}}^{\text{NR}} + \frac{P_{h_{S}}}{P_{h_{AS}}} = \mathcal{P}_{h_{AS}} (N_s - 1) + \mathcal{L}(\mu_{P_{AS}} + \beta \mu_{P_{RS}} + \mu_{0} \sqrt{\beta \mu_{P_{AS}} \mu_{P_{RS}}}),$$ (26)

where $\mu_{0} \triangleq \cos\left(\frac{2\pi (d_{AS} - d_{RS})}{\lambda}\right) = \left(\frac{K+1}{K}\right)I_0\left(\frac{K}{\lambda}\right) + K I_1\left(\frac{K}{\lambda}\right)$

and $\mathcal{P}_{h_{S}} - \mathcal{P}_{h_{AS}} = 1 - \gamma_S$, $\mathcal{P}_{h_{S}} = P_{h_{S}} N_s$ and $\mathcal{P}_{h_{AS}} = P_{h_{AS}}$. Using (26) and discussion in Sections III-C and IV-B, $P_{IS}$ using harvested energy $E_{h_{S}}^{\text{ER}}$ over $N_s$ slots is:

$$P_{IS} = E_{h_{S}}^{\text{ER}} - P_{\text{con}} = \mathcal{P}_{h_{AS}} (N_s - 1) + \mathcal{L}(\mu_{P_{AS}} + \beta \mu_{P_{RS}} + \mu_{0} \sqrt{\beta \mu_{P_{AS}} \mu_{P_{RS}}}) + C - \mathcal{P}_{h_{AS}} \nu_{j} \in \{1 \leq j < N_s\} \land \left(\mathcal{P}_{h_{S}} + \beta \mu_{P_{RS}} + \mu_{0} \sqrt{\beta \mu_{P_{AS}} \mu_{P_{RS}} \leq \mathcal{P}_{h_{S}} + 1}\right).$$ (27)

Next, we present an important result on utility of ER mode based on the variation of $\alpha$.

**Lemma 1:** With $E_{h_{S}}^{\text{ER}} > P_{\text{con}}$, the transmit power $P_{IS}$ of $S$ based on its harvested energy $E_{h_{S}}^{\text{ER}}$ via RF-ET from $A$ and $ER$ from $R$ is either: (i) concave increasing function of $\alpha$ when energy signals received at $S$ in the $N_s$th slot from $A$ and $R$ add up constructively, or (ii) strictly-convex in $\alpha$ when energy signals from $A$ and $R$ lead to destructive interference.

**Proof:** First of all we note that, the value of $\mu_{0}$ containing cosine term $\cos(\cdot)$ represents constructive or destructive interference of energy signals from $A$ and $R$. $\mu_{0} > 0$ always leads to constructive interference, i.e., $E_{h_{S}}^{\text{ER}} > E_{h_{S}}^{\text{NR}}$. However if $\mu_{0} < 0$, then received energy signals at $S$ in $N_s$th slot may add up destructively to cause $E_{h_{S}}^{\text{ER}} < E_{h_{S}}^{\text{NR}}$.

As $\frac{\partial^2 P_{IS}}{\partial \alpha^2} = -\mu_{0} M_{1} \sqrt{\alpha \beta \mu_{AS} \mu_{P_{RS}}}$, we can observe that $P_{IS}$ is concave in $\alpha$ if $\mu_{0} \geq 0$; otherwise it is a convex function of $\alpha$ $\forall \mu_{0} < 0$. We also note that, since $\frac{\partial^2 P_{IS}}{\partial \alpha^2} = \frac{1}{2} \beta \mu_{P_{RS}} M_{j} \left(\frac{\sqrt{\alpha \beta \mu_{AS} \mu_{P_{RS}}}}{\mathcal{P}_{h_{AS}} + 1}\right)$. $P_{IS}$ strictly increasing function of $\alpha$ $\forall \mu_{0} \geq 0$ and $\beta = 1$. On other hand, if $\mu_{0} < 0$, a unique feasible critical point $\alpha_{\text{ER}} = \left\{\alpha \right\}$ ($\frac{\partial P_{IS}}{\partial \alpha} = 0 \land (0 \leq \alpha \leq 1)$ is defined as: $\alpha_{\text{ER}} \triangleq \frac{\alpha^{2} \mu_{P_{RS}}}{\mathcal{P}_{h_{AS}} \mu_{P_{RS}}}$.

Thus, for $\mu_{0} < 0$ if $\alpha \leq \alpha_{\text{ER}}$, then $P_{IS}$ is a decreasing function of $\alpha$. However when $4\alpha_{\text{ER}} < \alpha \leq 1$, $P_{IS}$ is an increasing function of $\alpha$ and even for $\mu_{0} < 0$, $\mathcal{L}(\mu_{P_{AS}} + \beta \mu_{P_{RS}} + \mu_{0} \sqrt{\beta \mu_{P_{AS}} \mu_{P_{RS}}}) > \mathcal{P}_{h_{AS}}$, which leads to the improved ER performance over NR.

**Remark 1:** Though $\mu_{0} < 0$ leads to destructive interference of signals from $A$ and $R$, i.e., $\mathcal{L}(\mu_{P_{AS}} + \beta \mu_{P_{RS}}) > \mathcal{L}(\mu_{P_{AS}} + \mu_{0} \mu_{\beta \mu_{P_{AS}} \mu_{P_{RS}}})$, $E_{h_{S}}^{\text{ER}} > E_{h_{S}}^{\text{NR}}$, if $\alpha > 4\alpha_{\text{ER}}$.

**Remark 2:** ER is always beneficial over NR $\forall \alpha > 0$ if $\mu_{0} \geq 0$ and $\forall \alpha > 4\alpha_{\text{ER}}$ if $\mu_{0} < 0$.

Hence, we conclude that ER is preferred over NR when energy signals received at $S$ from $A$ and $R$ are combined constructively. The chances of ER performing better than NR increase with increasing $P_{IS}$ which leads to a higher $\mu_{P_{RS}}$ because it helps in meeting the condition $\alpha > 4\alpha_{\text{ER}}$.

B. Feasibility of Information Relaying (IR) Mode

Now we obtain the feasibility conditions for improved performance of IR over NR mode.

**Lemma 2:** The normalized delay-limited throughput $\tau$ in IR is more than NR if and only if one of these two conditions hold: (i) $p_{\text{out}}^{\text{IR}} < p_{\text{out}}^{\text{NR}}$, or (ii) $p_{\text{con}}^{\text{IR}} < p_{\text{con}}^{\text{NR}}$. 

**Proof:** Firstly, $\tau_{\text{IR}} = \frac{(N_s-1)(1-p_{\text{out}}^{\text{IR}})}{2N_s(N_s-1)(1-p_{\text{out}}^{\text{IR}})}$, and $\tau_{\text{NR}} = \frac{(N_s-1)(1-p_{\text{out}}^{\text{NR}})}{2N_s(N_s-1)(1-p_{\text{out}}^{\text{NR}})}$.

For $\tau_{\text{IR}} > \tau_{\text{NR}}$, we require $p_{\text{out}}^{\text{IR}} > p_{\text{out}}^{\text{NR}}$. For $\tau_{\text{IR}} > \tau_{\text{NR}}$, either $p_{\text{out}}^{\text{IR}} < p_{\text{out}}^{\text{NR}}$ or $p_{\text{con}}^{\text{IR}} < p_{\text{con}}^{\text{NR}}$. As $p_{\text{con}}^{\text{IR}} = Pr(\gamma_{S} < 2R_{0} - 1)$ and $p_{\text{out}}^{\text{IR}} = Pr(\gamma_{S} < 2R_{0} - 1)$, it is worth noting that the outage threshold of $2R_{0}$ for IR is twice the outage threshold $R_{0}$ for NR. Following this result, we next discuss the conditions where outage probability $p_{\text{out}}^{\text{IR}}$ in IR and $i^2$ER modes is better than outage probability $p_{\text{out}}^{\text{NR}}$ in no IR modes, namely NR and ER.
Lemma 3: To ensure that $p_{\text{out}}^R < p_{\text{out}}^\text{noIR}$, the following average SNR conditions should be met: (i) $E[\gamma_{SR}] > E[\gamma_{SA}] \left( E[\gamma_{SA}] + 2 \right)$ and (ii) $E[\gamma_{RA}] > E[\gamma_{SA}] \left( 1 + E[\gamma_{SA}] \right)$.

Proof: Please refer to Appendix A.

Remark 3: With $E[\gamma_{SA}] > 0$, Lemma 3 implies that for feasibility of IR, $E[\gamma_{SR}] > E[\gamma_{SA}]$. Or, IR is feasible when $\mathcal{R}$ is placed relatively closer to $S$ to strengthen $S$-to-$\mathcal{R}$ link.

Corollary 1: Outage performance for IR is better than NR if relay placement (RP) $(d_{SR}, d_{RA})$ lies in the set $S_{\text{IR}} \triangleq \left\{ (d_{SR}, d_{RA}) \left| d_{SR} < d_{SA} \left( 2 + E[\gamma_{SA}] \right) \right\} \land (d_{RA} < d_{RA}^\text{max}) \right\}$.

Proof: From Lemma 3, we note that to ensure $p_{\text{out}}^R < p_{\text{out}}^\text{noIR}$, two average SNR conditions (i) and (ii) should be met. Condition (i) on simplification results in the following relationship between $S$-to-$\mathcal{R}$ and $S$-to-$A$ distances:

$$d_{SR} < \frac{\left( 2 + \left( \frac{\alpha h_{SR} - \alpha h_{SR}}{2} \right) G_{SA} G_{R} \right) \left( 1 + \frac{\alpha h_{SR} - \alpha h_{SR}}{2} \right) \left( 1 + \frac{\alpha h_{SR} - \alpha h_{SR}}{2} \right)}{\pi} = \frac{d_{SA}^\text{max}}{\left( 2 + E[\gamma_{SA}] \right)}.$$

Similarly, condition (ii) puts an upper bound $d_{RA}^\text{max}$ on $\mathcal{R}$-to-$A$ distance $d_{RA}$ to meet the EH requirements of $\mathcal{R}$ for efficient IR, which is given by: $d_{RA} < d_{RA}^\text{max} \triangleq \frac{16 \pi^2 (1 + \left( \frac{\alpha h_{SR} - \alpha h_{SR}}{2} \right) G_{SA} G_{R} \left( 1 - \alpha \right) E[\gamma_{SA}] + \left( 1 - \alpha \right) E[\gamma_{SA}] G_{SA}}{\pi G_{SA} G_{R}} = 1 \right\}.$

These bounds on $d_{SR}$ and $d_{RA}$ form the feasible RP set $S_{\text{IR}}$ for enhanced outage performance of IR over NR.

C. Insights on Optimal Mode Selection Policy

Using the observations in Sections V-A and V-B, now we provide insights on the mode to be selected among NR, ER, IR, and $i^2$ER based on the two decision making (cf. Fig. 2) for minimizing outage probability. From Lemma 2, improved outage performance in IR or $i^2$ER mode also implies that their throughput performance is better than ER or NR mode.

1) Decision I: IR or no IR?: From Lemma 3 and Corollary 1, we note that if relay placement $(d_{SR}, d_{RA}) \in S_{\text{IR}}$, then the outage probability $p_{\text{out}}^R$ in two-hop IT in IR and $i^2$ER modes is lower than the outage probability $p_{\text{out}}^\text{noIR}$ in single-hop IT in ER and NR modes. So with the available statistical CSI, decoding capability of $\mathcal{R}$ based on its harvested energy and $S$-to-$\mathcal{R}$ link quality is decided. Only when decoding capability is sufficiently large such that either of IR or $i^2$ER modes perform better than ER or NR modes, $\mathcal{R}$ invests its harvested energy on IR. Otherwise, it utilizes its energy for ER or saves it for future if a NR is chosen.

Further, as $i^2$ER with $\alpha = 0$ reduces to IR mode, the feasibility conditions for $i^2$ER mode are similar to as in IR mode, which are mentioned in Lemma 3. However, when both IR and $i^2$ER are feasible, i.e., $p_{\text{out}}^R < p_{\text{out}}^\text{noIR}$ for $\alpha = 0$, then $i^2$ER can provide better performance than IR by allowing integrated IR and ER, as discussed next.

2) Decision II: ER or no ER?: The decision for ER depends on whether the received energy signals from $A$ and $\mathcal{R}$ add constructively or destructively. The conditions for preferring ER over NR mode based on the value of $\alpha$ and $\mu_0$ have been presented in Lemma 1 and Remark 2.

When IR mode is feasible, then for $\mu_0 \geq 0$, $i^2$ER can provide better outage performance if $\frac{\partial E[\gamma_{SR}] + \gamma_{SA}}{\partial \alpha} \geq 0$. In other words, if both $E[\gamma_{SR}]$ and $E[\gamma_{RA} + \gamma_{SA}]$ are increasing in $\alpha$, then from Theorem 1 (Section VI-B), $p_{\text{out}}^R$ in $i^2$ER is a decreasing function of $\alpha$ implying that its outage performance with $\alpha > 0$ is better than that of IR mode having $\alpha = 0$.

VI. OPTIMAL SHARING OF HARVESTED ENERGY AT $\mathcal{R}$

Following the observations in previous section, now we optimize $\alpha$ to efficiently utilize the available harvested energy at $\mathcal{R}$ for ER and IR. First we formulate the optimization problem, followed by its generalized-convexity proof and the joint global-optimal solution ($R_0^\alpha, \alpha^*, \beta^*$).

A. Optimization Formulation

We intend to maximize the normalized throughput $\mathcal{T}$ by efficiently dividing harvested energy at $\mathcal{R}$ over $N_s$ slots, i.e., $\alpha$ fraction for ER and remaining $(1 - \alpha)$ fraction for IR. As $\mathcal{T}$ defined in (25) is a function of rate constraint $R_0$ bps/Hz to be met at $A$ during the IT phase of 1 or 2 slots, we also find maximum achievable rate $R_0$ that can be met with high probability $1 - p_{\text{out}}$, where $p_{\text{out}} \ll 1$. This is denoted by constraint C1 in throughput maximization problem (P1).

$$\begin{align*}
(P1) & : \text{maximize } \mathcal{T}, \quad \text{subject to: } \quad C1: p_{\text{out}} \leq p_{\text{th}}, \\
C2: & \alpha \geq 0, \quad C3: \alpha \leq 1, \quad C4: \beta \in \{0, 1\}.
\end{align*}$$

Here $\beta = 1$ or $\beta = 0$ is respectively based on whether to go for relaying (ER, IR, or $i^2$ER) or not (NR). As (P1) is nonconvex, it is difficult to jointly optimize $R_0, \alpha$, and $\beta$. So, we break the problem (P1) into two parts, i.e., first solve outage minimization problem (P2) to find optimal $\alpha$ that minimizes $p_{\text{out}}^R$. After that we use monotonicity of $p_{\text{out}}^R$ in $R_0$ to iteratively solve (P1).

$$\begin{align*}
(P2) & : \text{minimize } \alpha \quad \text{subject to: } \quad C2 \text{ and } C3.
\end{align*}$$

Remark 4: Using the statistical CSI along with the system parameters mentioned in Sections II, III, and IV, energy-rich $A$ solves (P1) and informs $\mathcal{R}$ and $S$ respectively about the optimal relaying mode ($\alpha^*, \beta^*$) and optimal $R_0^\star$ to maximize the normalized delay-limited throughput.

B. Generalized-Convexity of Outage Minimization Problem

Here we present some important results in the form of Lemma 4, Corollary 2, and Theorem 1, that will be useful in proving conditional generalized-convexity [33] of (P2).

Lemma 4: The average SNR $E[\gamma_{RA} + \gamma_{SA}]$ for $S$-$\mathcal{R}$-$A$ link is: (a) strictly concave in $\alpha$ if $\mu_0 > 0$ and (b) convex function of $\alpha$ for $\mu_0 \leq 0$ with unique stationary point denoted by $\alpha_{\text{gr}}$.

Proof: Using linearity of expectation in $E[\gamma_{RA} + \gamma_{SA}]$,

$$\begin{align*}
E[\gamma_{RA} + \gamma_{SA}] &= E[\gamma_{RA}] + E[\gamma_{SA}] = \frac{\mu_{\gamma_{SR}}}{\sigma^2} + \frac{\mu_{\gamma_{SA}}}{\sigma^2} \\
&= \left( 1 - \alpha \right) \frac{\mu_{\gamma_{SR}}}{\sigma^2} N_s + \left( 1 - \alpha \right) \frac{\mu_{\gamma_{SR}}}{\sigma^2} N_s - R_0 E[\gamma_{SA}] \\
&= \frac{\mu_{\gamma_{SR}}}{\sigma^2} (N_s - 1) + \frac{\mu_{\gamma_{SR}}}{\sigma^2} C_j - R_0 E[\gamma_{SA}] \left( G_{AR} \right) \left( d_{SA} \right)^{-\beta}, \\
\forall j \in \left\{ 1 \leq j \leq N \right\} \land \left[ \left( p_{\text{th}} \right) \left( G_{AR} \right) \left( d_{SA} \right)^{-\beta} \right] \leq \left( \frac{\alpha}{2} \right)^2,
\end{align*}$$

(30)
The global optimal utilization of harvested energy at relay

\begin{align}
\text{argmin}_{\alpha \in \{0,1\}, \mu_0 > 0, (g_{\text{err}}, a_{\text{err}}), \mu_0 \leq 0,} & \left\{ p_{\text{out}}^{\text{IR}} | a_{\text{out}} = 0 \right\} \\
\alpha_{\text{out}} & = \begin{cases} 
\alpha_{\text{out}}^{\text{min}}, & \alpha_{\text{cri}} < \alpha_{\text{out}}^{\text{min}} \\
\alpha_{\text{out}}^{\text{max}}, & \alpha_{\text{out}}^{\text{max}} \leq \alpha_{\text{cri}} \leq \alpha_{\text{out}}^{\text{max}}, \\
\alpha_{\text{out}}^{\text{max}}, & \text{otherwise}.
\end{cases}
\end{align}

Here \(\alpha_{\text{out}}^{\text{max}}\) is the maximum possible value for \(\alpha_{\text{out}}\), and \(\alpha_{\text{out}}^{\text{max}}\) is the maximum possible value for \(\alpha_{\text{cri}}\), which are both determined by the optimization problem.
Algorithm 1 Iterative scheme to maximize normalized throughput \( \bar{\tau} \) by jointly optimizing \( R_0, \alpha, \beta \)

**Input:** Relay position \((d_{R,A}, d_{R,S})\), system and channel parameters (cf. Section II), with tolerances \( p_{\text{out}}^i, \xi_0, \xi_0 \)

**Output:** Maximized throughput \( \tau^* \) along with optimal \( R_0^*, \alpha^*, \beta^* \)

**(A) Initialization**
1. Call Algorithm 2 to find \( \Upsilon_{\text{ER}} = \left\{ Y \mid p_{\text{out}}^i - F_{P_{\text{SR}}, A}(Y; K_{SA}, \frac{\mu_{PSG}}{\sigma^2}) \leq \xi \right\} \) for S-to-A link in ER mode with \( P_r = P_{R,A} \), \( \alpha = 1, \beta = 1 \), and \( p_{\text{out}} = p_{\text{out}}^0 \)
2. Call Algorithm 2 to find \( \Upsilon_{\text{NR}} = \left\{ Y \mid p_{\text{out}}^i - F_{P_{\text{SR}, A}}(Y; K_{SA}, \frac{\mu_{PSG}}{\sigma^2}) \leq \xi \right\} \) for S-to-A link in NR mode with \( P_r = P_{R,A} \), \( \alpha = 0, \beta = 0 \), and \( p_{\text{out}} = p_{\text{out}}^0 \)
3. Set \( i = 0 \), \( R_0(0) = \left( \frac{N_r + 2}{2(N_r + 1)} \right) \log_2 (1 + \max \{ \Upsilon_{\text{ER}}, \Upsilon_{\text{NR}} \}) \)

**(B) Recursion**
4. repeat (Main Loop)
5. Set \( i \leftarrow i + 1 \), \( \alpha_i^* \leftarrow \alpha^* \), which minimizes \( p_{\text{out}} \) for achieving rate \( R_0(i-1) \) in iER using Theorem 3
6. Call Algorithm 2 to find \( \Upsilon_{\text{RA}}(i) = \left\{ Y \mid p_{\text{out}}^i - (1 - \frac{1}{1 - \frac{F_{P_{R,A}}(Y; K_{RA}, \frac{\mu_{PSG}}{\sigma^2})}{1 - F_{P_{R,S,A}}(Y; K_{SA}, \frac{\mu_{PSG}}{\sigma^2})}}) \right\} \) \( \leq \xi \) in iER with \( P_r = \min\{ P_{S,R}, P_{R,A}, P_{R,S,A} \} \), \( \alpha = \alpha_i^*, \beta = 1, p_{\text{out}} = p_{\text{out}}^i \)
7. Set \( R_0(i) = \frac{1}{2} \log_2 (1 + Y_{\text{RA}}(i)) \)
8. until \( R_0(i) - R_0(i-1) \leq \xi_0 \)

**(C) Termination with Optimal Solution**
9. Set \( R_{O,1} = \log_2 (1 + \Upsilon_{\text{ER}}), R_{O,2} = \log_2 (1 + \Upsilon_{\text{NR}}), R_{O,3} = R_0(i) \)
10. Set \( j^* \leftarrow \arg \max_{1 \leq i \leq 3} R_{O,i} \), and optimal \( \{ R_0^*, \alpha^*, \beta^* \} \) is given by

\[
\begin{cases}
    \{ R_{O,1}, 1, 1 \}, & j^* = 1 \quad \text{(ER mode)} \\
    \{ R_{O,2}, 0, 0 \}, & j^* = 2 \quad \text{(NR mode)} \\
    \{ R_{O,3}, \alpha_i^*, 1 \}, & j^* = 3 \quad \text{(iER mode if \( \alpha_i^* = 0 \))}
\end{cases}
\]

with \( p_{\text{out}} \leq p_{\text{th}}^i \). Thus, with increasing iteration \( i \), \( \{ R_0(i) \} \) monotonically increases (i.e., \( R_0(i+1) > R_0(i) \)) because of monotonically improving end-to-end SNR due to the optimal relaying mode selection for increasing \( \{ R_0(i) \} \).

**Fast Convergence of Algorithms 1 and 2:** Due to strict monotonicity and pseudoconvexity of \( p_{\text{out}} \) in \( R_0 \) and \( \alpha \) respectively, \( \alpha_i^* \) in each iteration can be found efficiently and in general Algorithm 1 converges to acceptable optimal solution \( R_0^* \) in two to three iterations only.

Similarly, Algorithm 2 employing a modified version of Newton-Raphson method, provides fast convergence to the inverse \( \Upsilon \) of CDF \( F_{P_{R,S}} \), where \( \Upsilon \) is defined in steps 1, 2, and 6 of Algorithm 1 for \( P_r \) in different relaying modes, due to the following properties: (i) \( F_{P_{R,S}} \) is monotonically increasing in \( \Upsilon \). (ii) \( F_{P_{R,S}} \) is continuously differentiable positive log-concave in \( \Upsilon \in [0, \infty) \). (iii) \( \frac{\partial F_{P_{R,S}}}{\partial \Upsilon} \) is continuously differentiable log-concave function of \( \Upsilon \). (iv) \( E\left[ F_{P_{R,S}} \right] \) provides a very good starting point. We noted that with conventional update equation \( \Upsilon(i) \leftarrow \Upsilon(i-1) + \frac{\Upsilon(i-1) - p_{\text{out}}^i}{F_{P_{R,A}}(\Upsilon(i-1), \beta; K_{SA}, \frac{\mu_{PSG}}{\sigma^2})} \) in standard Newton-Raphson method, iterations sometimes diverge. To overcome this drawback we consider the usage of log function with which convergence improves significantly. Via extensive numerical results, we have found that on average Algorithm 2 converges to acceptable tolerance \( \xi \) in less than 20 iterations.

**E. Some Additional Insights on Key System Parameters**

1) **Deciding \( N_s \) Slots Dedicated for RF-ET:** Since the end-to-end ET efficiency is very low, we need to allocate sufficient time for ET so that both \( S \) and \( R \) have sufficient harvested energy to carry out uplink IT at a desirable rate \( R_0 \). The rate of change of \( \Upsilon \) for NR mode with \( N_s \) is:

\[
\frac{\partial \Upsilon}{\partial N_s} = \frac{R_0}{(N_s + 1)^2} \left[ \left( 2R_0 - 1, K_{SA}, \frac{\mu_{PSG}}{\sigma^2} \right) \right], \quad i \left( 1 - F_{P_{R,S}}(2R_0 - 1, K_{SA}, \frac{\mu_{PSG}}{\sigma^2}) \right) \]  \tag{33}

From (33) we note that for low values of \( R_0, \frac{\partial \Upsilon}{\partial N_s} < 0 \), implying that \( \Upsilon \) in NR is a decreasing function of \( N_s \) because for low \( R_0 \), PDF \( f_{P_{R,S}} \) is lower than CCDF \( 1 - F_{P_{R,S}} \) and thus \( N_s \) can be set as the minimum, i.e., 2 slots. However if \( R_0 \) is high for meeting the demands of high QoS applications, then \( \Upsilon \) initially increases till \( N_s = N_s^* \) and for \( N_s > N_s^* \) it decreases with increased \( N_s \). Here the optimal \( N_s \) for NR, denoted by \( N_s^* \), is obtained by solving \( \frac{\partial \Upsilon}{\partial N_s} = 0 \).
2) Insights on Optimal Relay Placement (ORP): Although this work focuses on solving the dilemma of $R$ on whether to cooperate in downlink ER to $S$ or uplink IR to $A$ based on its relative placement between $A$ and $S$, here we give insights on ORP for different relaying modes.

For ER mode, detailed investigation on the ORP in two-hop RF-ET was carried out in [5]. It was observed that ORP, always lying in the constructive interference region, depends on the end-to-end distance $d_{AS}$. If $d_{AS}$ is relatively low then ORP lies in the constructive interference region closer to the RF-EH device $S$, whereas if $d_{AS}$ is relatively high then ORP lies closer to RF source $A$. We have obtained similar results as plotted in Fig. 6 and discussed in Section VII-B.

Regarding IR mode, it is difficult to obtain the closed-form results for ORP due to high composite non-linearity. However by exploiting the behavior of DF-IR protocol, we provide a suboptimal RP solution that provides tight approximation to the global-ORP. As the DF-IR performance is bottlenecked by the minimum of the SNR of $S$-to-$R$ link and the SNR due to MRC, we present a suboptimal RP that improves the SNR of the bottleneck link by making the two SNRs equal. This RP solution is obtained by solving $E[\gamma_{SR}] = E[\gamma_{SA} + \gamma_{RA}]$. Further as $E[\gamma_{SR}] > E[\gamma_{RA}]$, $R$ is placed closer to $S$ to ensure $E[\gamma_{SR}] > E[\gamma_{RA}]$. The goodness of this suboptimal solution providing insights on the features of the global optimal RP solution is investigated numerically in Section VII-B.

Finally with the above discussions on ORP in ER and IR, we note that the ORP in i2ER not only lies closer to $S$ to ensure efficient IR but also it should fall in the constructive interference region to ensure efficient ER. This claim is also numerically validated later in Section VII-C.

VII. NUMERICAL RESULTS AND DISCUSSION

We conduct numerical investigation on performance of WPON under different relaying options: NR, ER, IR, or i2ER. Unless otherwise stated, the considered system parameters are: $P_{th} = 30$ dBm, $G_A = G_S = 1$ dBi, $G_R = 6.1$ dBi, $\sigma^2 = -100$ dBm, $\lambda = 0.328$ m, $\nu_p = \{0.25, 0.05\}$ m [5] for $d_{AS} = \{1, 2\}$ m, $N = 2$, $T = 1$, $\varphi = 0.175$ rad [5], $P_{th} = 0$ W, $E_{tot} = 0.927$ mJ [26], $E_{tot} = 93.53 \mu J$ [26], $E_R = 0$ J, $K = 10$ dB for all the links, and tolerances as $\xi_{th} = 10^{-3}$, $\xi = 10^{-6}$.

Using (1), the piecewise linear approximation $P_{th} = L(P_{r})$ for $P_{th}$ (in mW) at the output of the commercially available Powercast P1110 RF harvester [24] can be obtained with $P_{th} = \{0.282, 0.501, 1.0, 3.548, 25.119, 100\}$ mW as six received threshold powers dividing the harvested received power characteristic of P1110 into $N = 5$ linear pieces having slope $M = \{0.857, 0.786, 0.485, 0.733, 0.465\}$ and intercept $C = \{-0.223, -0.194, 0.107, -0.772, 5.948\}$ mW.

The accuracy of approximation (1) can be observed from the fact that root mean square error (RMSE) in approximating the measured results given in [5, Fig. 5(b)] is less than 0.0003 and corresponding R-square statistics value is more than 0.9997.

A. Validation of Analysis

First, we validate the analytical expression for $E_{h,as}^{ER}$ derived using (8) and (12). Analytical results in Fig. 3 are generated using only first 30 summands of series in (8). The simulation results on mean harvested power at $S$ for varying relay position ($x_{AS}, 0.25$ m) and $N_s$ are generated by finding mean of $10^7$ random realizations of harvested dc power $P_{h,as}$ obtained by applying (1) on random received power $P_{r,as}$ following noncentral-$\chi^2$ distribution. A close match between analytical and simulation results as observed in Fig. 3 validates the analysis in Section III with a RMSE of less than $10^{-4}$. From Fig. 3 it is observed that, in comparison to energy harvested $E_{h,as}^{ER}$ in no ER case, $E_{h,as}^{ER}$ in ER is affected by constructive and destructive interference of energy signals received from $A$ and $R$. However with increasing $N_s$, the destructive interference region decreases due to increased $E_{h,as}$, which results in improved ER gain with higher RF-ET from $R$.

Next we validate the outage analysis carried out in Section IV. We have considered only first 30 summands for each of the three series in (20) for generating analytical results depicted by solid line in Fig. 4 and different line styles in Fig. 5. We first validate expression (20) for CDF of sum of two weighted noncentral-$\chi^2$ random variables in Fig. 4 for different values of Rice factor $K$ and means $\mu_{P_1}$ and $\mu_{P_2}$. After that analytical expression (22) for $p_{out}^{IR}$ is validated in Fig. 5. Monte-Carlo simulation results matching closely with

Fig. 3: Variation of $E_{h,as}^{ER}$ with relay position ($x_{AS}, 0.25$ m) and $N_s$.

Fig. 4: Validation of expression (20) for CDF of sum of two weighted noncentral-$\chi^2$ random variables.

Fig. 5: Variation of $p_{out}$ in IR and NR with $x_{AS}, d_{AS}$, $N_s$, $R_0$. $R_0$ is respectively 14 and 12 bps/Hz for $d_{AS}$ as 1 and 2 m.
normalized results, with a RMSE of 0.0031 and 0.00034 for results plotted in Figs. 4 and 5, validate the analysis for $F_{\mathcal{R}_1} + F_{\mathcal{R}_2}$ and $P_{\text{out}, \text{ir}}$, respectively. Results plotted in Fig. 5 show that, $\mathcal{R}$ is advantageous over NR only when $\mathcal{R}$ is closer to $\mathcal{S}$ than $\mathcal{A}$, i.e., $\frac{d_{\mathcal{R} \mathcal{A}}}{d_{\mathcal{R} \mathcal{S}}} > \frac{1}{2}$. Minimum $P_{\text{out}, \text{ir}}$ is achieved when $\mathcal{R}$ is very close to $\mathcal{S}$. We also note that outage performance is improved with increasing $N_s$ due to increase in $P_{\text{tx}, s}$, which enhances quality of $\mathcal{R}$-to-$\mathcal{A}$ IT link.

B. Energy Relaying versus Information Relaying

We now compare the achievable normalized throughput $\tau$ performance of $\mathcal{R}$ with IR in Figs. 6(a) and 6(b) for varying $x_{\mathcal{R}}, d_{\mathcal{AS}}, R_0$ (in bps/Hz) with $N_s = 5$ and $N_s = 10$, respectively. Results plotted in Fig. 6(a) show that $\tau$ for $\mathcal{R}$ mode is more than that of $\mathcal{E}$ mode if: (a) $x_{\mathcal{R}} > 0.58$ m for $d_{\mathcal{AS}} = 1$ m and (b) $1.05 < x_{\mathcal{R}} < 1.6$ m for $d_{\mathcal{AS}} = 2$ m. Similarly for $N_s = 10$ as plotted in Fig. 6(b), $\tau$ in IR is more than that of $\mathcal{R}$ for $\forall x_{\mathcal{R}} > 0.48$ m if $d_{\mathcal{AS}} = 1$ m and $\forall x_{\mathcal{R}} > 0.99$ m if $d_{\mathcal{AS}} = 2$ m. This shows that $\mathcal{E}$ is better than IR if $\mathcal{R}$ is positioned closer to $\mathcal{A}$, and vice-versa. Further, the ORP for IR is very close to information source $\mathcal{S}$. Whereas ORP in $\mathcal{E}$, which is affected by continuous constructive-destructive interference cycles, is very close to $\mathcal{S}$ for $d_{\mathcal{AS}} = 1$ m, and it is very close to $\mathcal{A}$ for $d_{\mathcal{AS}} = 2$ m. From Fig. 6(a) we also notice that when $\mathcal{R}$ is placed very close to $\mathcal{S}$, it may lead to weakening of $\mathcal{R}$-to-$\mathcal{A}$ link, and hence violating the upper bound $d_{\mathcal{R}, \mathcal{A}}^{\text{max}}$. This leads to the degraded IR performance in comparison to $\mathcal{E}$ (or NR) as mentioned in Lemma 3 and Corollary 1. For the four considered combinations of $(N_s, d_{\mathcal{AS}}) = \{(5, 1), (5, 2), (10, 1), (10, 2)\}$, the numerically obtained optimal throughput being $\tau = \{3.8587, 3.2803, 2.3240, 1.9923\}$ bps/Hz. The corresponding suboptimal RP solutions $x_{\mathcal{R}}^{\text{opt}}$ and their respective throughput $\hat{\tau}$ are given by $x_{\mathcal{R}}^{\text{opt}} = \{0.76, 1.44, 0.78, 1.52\}$ m and $\hat{\tau} = \{3.8586, 3.2802, 2.3239, 1.9921\}$ bps/Hz. Thus, the difference in throughput performance of suboptimal RP for IR mode is less than 0.0071%.

C. Efficient Utilization of Harvested Energy at $\mathcal{R}$

In Fig. 7, we plot the variation of $\tau$ with relay position $(x_{\mathcal{R}}, y_{\mathcal{R}}) = 0.25$ m and $\alpha$ for $R_0 = 14$ bps/Hz. Results show that for lower $x_{\mathcal{R}}$, $\alpha = 1$ is optimal which implies that ER is a better mode for low $x_{\mathcal{R}}$. As $x_{\mathcal{R}}$ increases and goes beyond 0.42 m, optimal $\alpha$ reduces and is equal to zero (IR) for destructive interference cycle and $\alpha \neq 0$ for constructive cycle (cf. zoomed plot in Fig. 6(b)). Fig. 7 shows that joint optimal solution that maximizes $\tau$ in $i^2$ER is $(\alpha^* = 0.02, x_{\mathcal{R}}^* = 0.76m)$. This implies that, if relay position is controllable then $\mathcal{R}$ should be placed close to $\mathcal{S}$ with higher share of harvested energy at $\mathcal{R}$ allocated for $\mathcal{R}$. Also, the difference in throughput performance of the suboptimal RP is 0.756 m, which is less than 0.0034%.

In Fig. 8, we plot the optimal relaying mode along with achievable $\tau$ for varying $x_{\mathcal{R}}$. Considering four combinations of $(N_s, d_{\mathcal{AS}}) = \{(5, 1), (5, 2), (10, 1), (10, 2)\}$, $R_0 = \{23, 19, 24, 20\}$ bps/Hz for NR and $\mathcal{E}$, and $R_0 = \{13.6, 11.6, 14, 12\}$ bps/Hz for $\mathcal{R}$ and $i^2$ER. These values are based on maximum $R_0$ achievable in each mode such that resulting $p_{\text{out}} \leq 10^{-2}$. When $\mathcal{R}$ is close to $\mathcal{S}$, i.e., $x_{\mathcal{R}} < 0.44$, there are only two optimal modes possible: $\mathcal{E}$ for constructive interference regions and NR for destructive interference regions. In contrast, as shown in Fig. 8, $\mathcal{R}$ or $i^2$ER is selected as optimal mode when $\mathcal{R}$ is close to center or $\mathcal{S}$. When $N_s$ is sufficiently high and $\mathcal{R}$ is placed close to $\mathcal{S}$, WPCN can benefit from both $\mathcal{E}$ and $i^2$ER. $i^2$ER mode is optimal in constructive regions. $\mathcal{R}$ is optimal when $\mathcal{R}$ is close to $\mathcal{S}$ and $d_{\mathcal{AS}}$ is large which leads to need for alternate IR link due to weakening of $\mathcal{S}$-to-$\mathcal{A}$ link.

For the relay positions in Fig. 8 where NR was selected (as denoted by “×” mark), we next investigate the effect of energy accumulation at $\mathcal{R}$ due to the unused harvested energy.
TABLE II: Investigating the effect of energy accumulation at $R$ during the NR modes plotted in Fig. 8.

<table>
<thead>
<tr>
<th>I: $N_s = 5$, $d_{AS} = 1$ m</th>
<th>II: $N_s = 10$, $d_{AS} = 1$ m</th>
<th>III: $N_s = 5$, $d_{AS} = 2$ m</th>
<th>IV: $N_s = 10$, $d_{AS} = 2$ m</th>
</tr>
</thead>
<tbody>
<tr>
<td>S. No.</td>
<td>$x_R$ (m)</td>
<td>Mode</td>
<td>Blocks</td>
</tr>
<tr>
<td>1</td>
<td>0.20</td>
<td>ER</td>
<td>5</td>
</tr>
<tr>
<td>2</td>
<td>0.22</td>
<td>ER</td>
<td>5</td>
</tr>
<tr>
<td>3</td>
<td>0.24</td>
<td>ER</td>
<td>5</td>
</tr>
<tr>
<td>4</td>
<td>0.26</td>
<td>ER</td>
<td>2</td>
</tr>
<tr>
<td>5</td>
<td>0.50</td>
<td>ER</td>
<td>2</td>
</tr>
<tr>
<td>6</td>
<td>0.52</td>
<td>ER</td>
<td>4</td>
</tr>
<tr>
<td>7</td>
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<td>ER</td>
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<td>0.56</td>
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<td>7</td>
</tr>
<tr>
<td>9</td>
<td>0.58</td>
<td>ER</td>
<td>6</td>
</tr>
<tr>
<td>10</td>
<td>0.60</td>
<td>ER</td>
<td>4</td>
</tr>
</tbody>
</table>

Fig. 9: Enhancement in $p_{out}$ and $\tau$ for IR, ER, and $i^2$ER over NR.

D. Investigating the Impact of Advanced RF-EH Circuits

Now we investigate performance of the proposed protocol and optimized solutions for larger end-to-end RF-ET range $d_{AS}$ achieved with the help of advanced RF-EH circuits which are currently under research [22], [23] and will be available commercially in future. With these advancements in RF-EH technology, we can efficiently harvest input RF powers as low as $-20$ dBm at a rectification efficiency of 0.5 (or 50%). Also this RF-to-dc rectification efficiency does not degrade and can be maintained constant at 0.5 for all RF input powers $\geq -20$ dBm. With this setting, RF-ET range $d_{AS}$ can be improved from 2 m to 10.3 m. For this improved RF-ET range we have plotted the optimal relaying mode along with maximum normalized throughput $\tau^*$ for varying relay positions and $R_0$ in Fig. 10. Here we have also considered setting $N_s$ as $N_s^*$ to meet a rate requirement of at least $R_0$ with high probability greater than 0.99 even for NR mode. Following the discussion in Section VI-E1, $N_s^*$ is respectively obtained as 35 slots and 140 slots for $R_0 = 12$ bps/Hz and $R_0 = 14$ bps/Hz.

Results plotted in Fig. 10 show that, for larger $d_{AS} = 10.3$ m the performance of both ER and IR gets affected. On one hand, the gap between ER and NR is reduced due to decrease in ER efficiency because of low energy harvested at $R$. On the other hand, the energy $E_{IR}$ that is available at the beginning of future transmission block(s) of these NR cases. The corresponding results showing the number of NR transmission blocks after which a relay position becomes suitable for relaying (ER/IR) due to accumulated energy are tabulated in Table II. The optimal relaying mode that is eventually selected for utilizing all the accumulated energy over previous NR blocks is also listed.
larger A-to-R distance and low energy delivered to S over larger R-to-S distance. Whereas, the performance of IR and i²ER with low $N_s^* = 35$ slots is poorer than ER for $R_0 = 12$ bps/Hz because energy harvested at R over $N_s^*$ slots for larger A-to-R distances, denoted by larger $x_R$, is not sufficient to meet the decoding costs. However when $N_s^* = 140$ slots for meeting $R_0 = 140$ bps/Hz, IR and i²ER perform better than ER even for larger A-to-R distances because now the energy harvested over such large number of slots is sufficient for meeting the decoding costs.

E. Performance for Jointly-Optimized ($R_0^*, \alpha^*, \beta^*$) in (P1)

Now we investigate the maximum normalized throughput $\tau^*$ performance achieved by jointly optimizing ($R_0^*, \alpha^*, \beta^*$) in (P1) for different QoS requirements represented in terms of varying outage probability threshold $p_{out}^{th} = \{10^{-2}, 10^{-3}, 10^{-4}, 10^{-5}, 10^{-6}\}$. Variation of optimized $\tau^*$ along with optimal mode with $p_{out}^{th}, x_R, N_s, \text{and } d_{AS}$ is plotted in Fig. 11. It is observed that $\tau^*$ for $p_{out}^{th} = 10^{-5}$ is 13.29% lower than for $p_{out}^{th} = 10^{-3}$ due to reduced $R_0^*$. Comparing with results in Fig. 8 having fixed $R_0$, results in Fig. 11 with optimized $R_0^*$ show that with decreasing $p_{out}^{th}$ (stricter QoS requirement), IR and i²ER modes become more useful for meeting high $R_0$ requirements. The corresponding optimal $\alpha^*$ is plotted in Fig. 12 for $d_{AS} = 1$ m. Optimal $\alpha^*$ for $d_{AS} = 2$ m is noted in Fig. 11 itself with NR, ER, and IR having optimal ($\alpha^*, \beta^*$) as ($-0$), (1, 1), (0, 1), respectively. From Figs. 11 and 12, it is observed that in general optimal $\alpha^*$ decreases with increased distance $d_{AS} = \sqrt{x_R^2 + y_R^2}$ between A and R, except during destructive interference cycle (cf. Figs. 6(a) and 6(b)) where $\alpha^* = 0$. From Fig. 12 it also is noted that optimal $\alpha^*$ in i²ER for $d_{AS} = 1$ m increases with decreased $p_{out}^{th}$.

Next, we investigate the tradeoff between the optimized $\tau^*$ and acceptable outage probability (QoS) requirement $p_{out}^{th}$.

Results plotted in Fig. 13 for $d_{AS} = 1$ m show that achievable normalized throughput $\tau^*$ respectively decreases by 30.9% and 28.3% for $N_s = 5$ and $N_s = 10$ slots when $p_{out}^{th}$ is increased from $10^{-2}$ to $10^{-6}$. Further it is also noted that R placed closer to S (i.e., higher $x_R$) helps in achieving higher $\tau^*$, with $N_s = 5$ providing higher $\tau^*$ than $N_s = 10$ slots.

Finally, we present the throughput performance enhancement results achieved with the help of optimized i²ER model over the benchmark WPCN model with NR. Results plotted in Fig. 14 show that improvement in optimal $\tau^*$ increases monotonically with increased QoS requirement (i.e., decreased $p_{out}^{th}$) for all four combinations of $(N_s, d_{AS})$. In fact as $p_{out}^{th}$ decreases from $10^{-2}$ to $10^{-6}$, optimized i²ER improves the throughput performance of NR from 10% to up to 30%.

VIII. CONCLUDING REMARKS

This paper has investigated efficient utilization of harvested energy at RF harvesting relay R for either downlink ER, or uplink IR, or i²ER, to maximize the normalized throughput $\tau$ for information transfer from an energy-constrained source S to an energy-surplus HAP A. While considering i²ER, closed-form expressions for mean harvested energy at S and outage probability at HAP A with MRC over Rician channels have been derived. Using these expressions, analytical insights on optimal relaying mode have been provided along with global-optimal sharing of harvested energy at R for maximizing $\tau$ while ensuring very low outage probability $p_{out}^{th}$ in achieving rate $R_0$. The analysis has been validated by simulation results. Via numerical investigation it has been observed that, when $R$ is close to $A$, ER and NR are the optimal modes. On other hand, when $R$ is close to $S$, IR and i²ER are more beneficial. In general, $R$ positioned closer to $S$, with higher share of harvested energy allocated for IR, provides higher $\tau$. Overall in comparison to benchmark NR mode, i²ER having advantages of both IR and ER offers an average outage improvement of 22% for fixed $R_0$ and up to 30% improvement in $\tau$ by jointly-optimizing ($R_0^*, \alpha^*, \beta^*$) for $p_{out}^{th} = 10^{-6}$. Thus, this paper provides a benchmark for further investigation on optimized i²ER aspects for improving the performance of WPCNs.

**APPENDIX A**

**PROOF OF LEMMA 3**

From (22), \(P_{out}^{IR} = 1 - F_{PSR} - F_{PSR} \cdot F_{PSRA} + F_{PSRA} \), where \(F_{PSR} \pm 1 - F_{PSR} \cdot (2^{\alpha R_0 - 1, KSR}, \frac{\mu}{\sigma^2} F_{PSRA} + F_{PSRA} \pm 1 - \)
Given by:

\[ \mathbb{E}[\gamma_{SR}] = \frac{\mu_{PSR}}{\mu_{PSR}} \]

For all random variable \( F \), we have:

\[ \Pr[F \leq r] \leq \exp \left( \frac{-r^2}{2\sigma^2} \right) \]

We consider an alternative, from Jensen’s inequality [35] for expectation of concave transformation \( g(\cdot) \) of random variable \( X \), we see that \( \mathbb{E}[g(X)] \leq g(\mathbb{E}[X]) \). As \( \log(\cdot) \) is an increasing concave function, \( \mathbb{E}[\log(2 + \gamma_{SR})] \leq \frac{1}{2} \log(2 + \gamma_{SR}) \). Since it is difficult to obtain closed-form expression for \( \mathbb{E}[\log_2 (2 + \gamma_{SR})] \), we consider an order statistic. For random variable \( \gamma_{SR} \), we consider a positive increasing function \( \Phi(\gamma_{SR}) \) such that \( \Phi(0) = 0 \) and \( \Phi'(\gamma_{SR}) > 0 \).

Now we prove part (ii) of the lemma. As \( \mathbb{E}[\log_2 (2 + \gamma_{SR})] \leq \frac{1}{2} \log(2 + \gamma_{SR}) \), \( \mathbb{E}[\log_2 (2 + \gamma_{SR})] \) is a positive increasing function.

Next we prove log-concavity of \( \mathbb{E}[\gamma_{SR}] \) in \( \mathbb{E}[\gamma_{SR}] \). We show that for all random variable \( \gamma_{SR} \), we have:

\[ \mathbb{E}[\gamma_{SR}] = \frac{\mu_{PSR}}{\mu_{PSR}} \]

We consider an alternative, from Jensen’s inequality [35] for expectation of concave transformation \( g(\cdot) \) of random variable \( X \), we see that \( \mathbb{E}[g(X)] \leq g(\mathbb{E}[X]) \). As \( \log(\cdot) \) is an increasing concave function, \( \mathbb{E}[\log(2 + \gamma_{SR})] \leq \frac{1}{2} \log(2 + \gamma_{SR}) \). Since it is difficult to obtain closed-form expression for \( \mathbb{E}[\log_2 (2 + \gamma_{SR})] \), we consider an order statistic. For random variable \( \gamma_{SR} \), we consider a positive increasing function \( \Phi(\gamma_{SR}) \) such that \( \Phi(0) = 0 \) and \( \Phi'(\gamma_{SR}) > 0 \).

Now we prove part (ii) of the lemma. As \( \mathbb{E}[\log_2 (2 + \gamma_{SR})] \leq \frac{1}{2} \log(2 + \gamma_{SR}) \), \( \mathbb{E}[\log_2 (2 + \gamma_{SR})] \) is a positive increasing function.

Next we prove log-concavity of \( \mathbb{E}[\gamma_{SR}] \) in \( \mathbb{E}[\gamma_{SR}] \). We show that for all random variable \( \gamma_{SR} \), we have:

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Proposition 1: For $\mu_0 \leq 0$, log-concavity of $F_{\mathbf{P}_R \mathbf{A} + \mathbf{P}_{\mathbf{S} A}} \cdot F_{\mathbf{P}_R \mathbf{A} + \mathbf{P}_{\mathbf{S} A}}$ in $\alpha$ may not hold, so following result is given.

Lemma 6: For $\mu_0 \leq 0$, $\alpha_{g_{R A}} \leq \alpha \leq \alpha_{g_{M A}}$, $\mathbf{F}_{\mathbf{P}_R \mathbf{S} R}$ is a pseudoconcave function of $\alpha$. Proof: To prove pseudoconcavity [34], we show that $\mathbf{F}_{\mathbf{P}_R \mathbf{S} R} \cdot \mathbf{F}_{\mathbf{P}_R \mathbf{A} + \mathbf{P}_{\mathbf{S} A}}$ is unimodal with respect to $\alpha$ given by:

$$c_{\alpha}^{\text{out}}(\alpha) = \left\{ \alpha \mid \sqrt{\alpha} = \frac{\mathbf{m}_\alpha \mathbf{P}_{\mathbf{P}_R} \mathbf{P}_{\mathbf{S} A}}{2} \left[ \mu_{\mathbf{P}_R} - \mathbf{P}_{\mathbf{S} A} - \mathbf{P}_{\mathbf{P}_R} \right]^{-1} \right\}$$

(C.3)

with $\Psi \geq \mu_{\mathbf{P}_R}$ to ensure $\sqrt{\alpha} \geq 0$. Here $\Psi \geq \mu_{\mathbf{P}_R}$ as defined below (C.3) in Lemma 6, is an increasing function of $\alpha \in [\alpha_{g_{M A}}, \alpha_{g_{M A}}]$ for $\mu_0 \leq 0$. Further, $\Psi$ is decreasing in $\alpha$. Further as $\sqrt{\alpha}$ is strictly increasing in $\alpha$, if $\exists \alpha_{c}^{\text{out}}(\alpha) \in [\alpha_{g_{M A}}, \alpha_{g_{M A}}]$, then it has to be unique because a strictly increasing and strictly decreasing function can cross each other only at a single point. This proves that $\mathbf{F}_{\mathbf{P}_R \mathbf{S} R} \cdot \mathbf{F}_{\mathbf{P}_R \mathbf{A} + \mathbf{P}_{\mathbf{S} A}}$ is positive pseudoconcave in $\alpha \in [\alpha_{g_{M A}}, \alpha_{g_{M A}}]$ for $\mu_0 \leq 0$. 

Proposition 1: For $\mu_0 \leq 0$, $\Psi$, as defined below (C.3) in Lemma 6, is an increasing function of $\alpha \in [\alpha_{g_{M A}}, \alpha_{g_{M A}}]$ because of the following reasons: (i) $\frac{\partial \mathbf{F}_{\mathbf{P}_R \mathbf{A} + \mathbf{P}_{\mathbf{S} A}}}{\partial \alpha}$ is a increasing function of $\alpha$, (ii) $\frac{\partial \mathbf{F}_{\mathbf{P}_R \mathbf{A} + \mathbf{P}_{\mathbf{S} A}}}{\partial \alpha}$ is decreasing in $\alpha$, (iv) $\frac{\partial \mathbf{F}_{\mathbf{P}_R \mathbf{S} R}}{\partial \alpha}$ is increasing in $\alpha$. 

Proof: From Theorem 1, we note that $\mathbf{F}_{\mathbf{P}_R \mathbf{S} R}$ and $\mathbf{F}_{\mathbf{P}_R \mathbf{A} + \mathbf{P}_{\mathbf{S} A}}$ are positive increasing log-concave functions of $\mathbb{E} [\gamma_{R A}]$ and $\mathbb{E} [\gamma_{R A} + \gamma_{S A}]$ respectively. Also, $\frac{\partial \mathbb{E}[\gamma_{R A}]}{\partial \alpha} = \frac{-G_A^2 \mu_{\mathbf{P}_R} \mathbf{P}_{\mathbf{S} A}}{\partial \alpha}$, which proves that $\mathbb{E} [\gamma_{R A}]$ is strictly decreasing in $\alpha$. Using these we observe that, though $\mathbf{F}_{\mathbf{P}_R \mathbf{A} + \mathbf{P}_{\mathbf{S} A}}$ is positive increasing function of $\mathbb{E} [\gamma_{R A}]$, its rate of increase is decreasing in $\mathbb{E} [\gamma_{R A}]$, i.e., $\frac{\partial \mathbb{E}[\gamma_{R A}]}{\partial \alpha}$ is decreasing function of $\mathbb{E} [\gamma_{R A}]$. Or in other words, $\frac{\partial \mathbb{E}[\gamma_{R A}]}{\partial \alpha}$ is decreasing function of $\alpha$ because $\mathbb{E} [\gamma_{R A}]$ is strictly decreasing function of $\alpha$. This proves part (i). Similarly, as $\mathbb{E} [\gamma_{S A}]$ is an increasing function of $\alpha$, $\frac{\partial \mathbb{E}[\gamma_{S A}]}{\partial \alpha}$ is decreasing function of $\alpha$, which proves part (ii). So, numerator of $\Psi$ is increasing in $\alpha$ because it is product of positive constant $\frac{\mathbf{F}_{\mathbf{P}_R \mathbf{A} + \mathbf{P}_{\mathbf{S} A}}}{\partial \alpha}$ and a positive increasing function $\frac{\partial \mathbf{F}_{\mathbf{P}_R \mathbf{A} + \mathbf{P}_{\mathbf{S} A}}}{\partial \alpha}$.

Next we show that denominator $G_{S \mu_{\mathbf{P}_R} M_3} \frac{\mathbf{F}_{\mathbf{P}_R \mathbf{A} + \mathbf{P}_{\mathbf{S} A}}}{\partial \alpha}$ is a decreasing function of $\alpha$ because $\mathbb{E} [\gamma_{R A}]$ is decreasing in $\alpha$ for $\mu_0 \leq 0$ and $\alpha \leq \alpha_{g_{M A}}$ (cf. Lemma 4). This proves part (iii) of Proposition 1. From Theorem 1, $\mathbf{F}_{\mathbf{P}_R \mathbf{S} R}$ is positive increasing function of $\mathbb{E} [\gamma_{R A} + \gamma_{S A}]$, and hence increasing function of $\alpha$ also because $\mathbb{E} [\gamma_{S A}]$ is increasing in $\alpha$. This proves part (iv). However its rate of increase is decreasing in $\mathbb{E} [\gamma_{S A}]$. Or in other words, $\frac{\partial \mathbb{E}[\gamma_{S A}]}{\partial \alpha}$ is decreasing function of $\alpha$ because $\mathbb{E} [\gamma_{S A}]$ is a strictly increasing function of $\alpha$, which proves part (v). Observing results (ii)–(v), along with the fact that sum and product of positive decreasing functions is also decreasing, we note that the denominator of $\Psi$ is decreasing in $\alpha$. Finally, as the ratio of positive increasing and decreasing functions is an increasing function, $\Psi$ with its numerator and denominator respectively being positive increasing and decreasing functions of $\alpha$ proves that $\Psi$ itself is positive increasing in $\alpha$.

Now we use the above two results to prove Theorem 2. From Lemma 5 we note that $\mathbf{F}_{\mathbf{P}_R \mathbf{S} R} \cdot \mathbf{F}_{\mathbf{P}_R \mathbf{A} + \mathbf{P}_{\mathbf{S} A}}$ is a positive log-concave function of $\alpha \in [0, 1]$, $\forall \mu_0 > 0$. Further as a positive differentiable log-concave function defined over a convex set is pseudoconcave in nature [13, Lemma 5], $\mathbf{F}_{\mathbf{P}_R \mathbf{S} R} \cdot \mathbf{F}_{\mathbf{P}_R \mathbf{A} + \mathbf{P}_{\mathbf{S} A}}$ is also pseudoconcave in $\alpha$, $\forall \mu_0 > 0$. From Lemma 6, we observe that $\mathbf{F}_{\mathbf{P}_R \mathbf{S} R} \cdot \mathbf{F}_{\mathbf{P}_R \mathbf{A} + \mathbf{P}_{\mathbf{S} A}}$ is pseudoconcave function of $\alpha \in [\alpha_{g_{R A}}, \alpha_{g_{M A}}]$. This proves that $p_{\text{out}} = 1 - \mathbf{F}_{\mathbf{P}_R \mathbf{S} R} \cdot \mathbf{F}_{\mathbf{P}_R \mathbf{A} + \mathbf{P}_{\mathbf{S} A}}$ is a positive pseudoconvex function of $\alpha \in [\alpha_{g_{R A}}, \alpha_{g_{M A}}]$ that minimizes $p_{\text{out}}$.

REFERENCES


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