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On Wireless Energy Harvesting based Relaying for Interference-limited User: A DMT perspective

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Abstract—In this paper, the diversity-multiplexing tradeoff (DMT) is investigated for an interference-limited relay-aided communication system in the moderate interference regime. Further, in the proposed system, the relay node is powered by wireless energy harvesting (WEH). In particular, this work studies the impact of energy harvest duration at the relay node on the achievable DMT of an interference-limited user using a variant of dynamic decode-and-forward based protocol. Our results show that the DMT of interference-limited user degrades with the proportional increase in energy harvest duration at low multiplexing gains. On the other hand, it is observed that the DMT of WEH-based interference-limited user approaches that of non-EH-based counterpart for higher multiplexing gains.

Index Terms—Diversity-multiplexing tradeoff (DMT), Dynamic decode-and-forward (DDF), Interference, Relays, Wireless energy harvesting

I. INTRODUCTION

The ever-increasing demand for constantly high data rates over a large coverage area has spurred the aggressive reuse of communication resources such as spectrum. However, frequency reuse introduces interference among users. Thus, maximizing the interference-limited user's throughput while meeting the Quality of Service (QoS) requirement is an important issue in the design of wireless systems. This problem can be addressed by utilizing other available nodes in the network as relays to support the affected interference-limited user [1]. The node cooperation consumes the battery of supporting nodes, hence affects the overall life-cycle of the network. This shortcoming can be remedied by the use of energy harvesting (EH), a process of scavenging energy from the ambient sources such as heat, light, and wind. However, the intermittent energy availability from such sources leads to complicated energy storage and scheduling issues. An elegant way to counter this is by using wireless EH (WEH) where the intermediate nodes harvest the energy from the source's transmitted signal. In recent times, WEH has gained significant attention because of its ubiquity and versatility making it an ideal candidate for supporting QoS based applications [2].

The system where the relay node receives data only from one of the sources has been considered in [3]–[5]. In [3], the authors have studied the sum-rate capacity using the full-duplex decode-and-forward relaying protocol. The finite-SNR performance was analyzed using the sum-rate capacity and the maximal generalized degrees-of-freedom in [4]. Ideally, full-duplex implementation supports higher throughput. However,

in practice, the self-interference (SI) emanates out of full-duplex operation deteriorates the signal-to-interference noise ratio (SINR), resulting in reduced data rates. Moreover, full-duplex system demands more hardware resources such as separate antennas for transmission and reception, circuitry to suppress the SI, and so on [6]. The half-duplex (HD) network significantly simplifies the implementation at the cost of spectral efficiency. In [7], authors provided the diversity-multiplexing tradeoff (DMT) analysis of a HD-based dynamic decode-and-forward (DDF) for a single relay channel. It is shown that the performance of HD-based DDF approaches that of an ideal full-duplex based decode-and-forward protocol. This fact motivated us to investigate the DMT performance of HD-based DDF for an interference-limited relay-aided system.

In [8], DMT has been characterized for WEH-based single relay channel using a variant of DDF protocol. Furthermore, the analysis has been extended for multiple relays in our previous work [9]. This renewed attention on WEH-based DDF motivated us to revisit the scheme for the interference-limited user. The DMT of the traditional interference channel (IC) with relay (ICR) has been extensively studied in the literature [10], [11]. However, to the best of our knowledge, the DMT for HD-based DDF has not yet been investigated for an interference-limited relay-aided scenario. Thus, in this work, we will first focus on the DMT of an interference-limited user employing a traditional non-EH-based relay using DDF protocol in the moderate interference regime. Subsequently, we extend our analysis for the system with a WEH-based relay. Finally, the performance of these systems is compared against classical reference schemes.

Note that the reason for choosing moderate interference regime is that it is essentially the worst among the three interference possibilities: weak, strong and moderate. In the weak interference scenarios, the interference can be treated as noise and can still decode the desired signal using interference ignorant decoder (IID). Similarly, in the strong interference regimes, successive interference cancellation (SIC) can decode and cancel the interference before decoding the intended signal. However, both these methods fail in the moderate interference regime where the intended signal and the interference are at the same level. In such scenarios, the joint decoder (JD) offers the best performance by simultaneously decoding the desired signal and the interfering signal [12]. In this work, we employ the JD in the proposed DMT analysis. To that end, the following are

Fig. 1. System Model with an energy harvesting based relay

II. SYSTEM MODEL

This work considers a system with two source nodes (S_1, S_2), two destination nodes (D_1, D_2), and two half-duplex relays (T_1, T_2) as shown in Fig. 1(a). In this, D_1 and D_2 are interference-limited users. The fading coefficients h_{ij} , $ij \in \{11, 13, 31, 21, 12, 22, 24, 42\}$ are assumed to be quasi-static, i.e., the path gains are constant over a codeword of length, l . The additive noises Z_1, Z_2, Z_3 , and Z_4 at different nodes are zero-mean, mutually independent, and white complex Gaussian. Further, it is assumed that the system is symmetric. Hence, as shown in Fig. 1(b), only the interference-limited user D_1 is considered for the DMT analysis.

In the case of WEH-based DDF protocol, the relay T_1 operates in three modes as shown in Fig. 1(b): energy harvesting, information decoding, and re-transmission using time-switching [13]. It harvests the energy and store it in a battery for the first l_h symbols, decodes the data from the source S_1 during l_d symbol transmissions, and after successful decoding, the information is forwarded to the destination D_1 by expending all the stored energy for the rest of the codeword duration ($l_t = l - l_h - l_d$). The fraction of energy harvest duration has been denoted by $\epsilon (= l_h/l)$. However, in the case of non-EH-based DDF, the energy harvesting phase is absent because the relay T_1 is powered by a fixed power source. Therefore, in this case, the harvest duration l_h is equal to zero.

The received signals at D_1 and T_1 at symbol interval i are denoted by $Y_{1,i}$, and $Y_{3,i}$ respectively. The channel inputs from source nodes S_1, S_2 , and relay T_1 at symbol interval i are denoted by $X_{1,i}, X_{2,i}$ and $X_{3,i}$, respectively. Thus, the relationship between the channel inputs and its outputs at symbol interval i is given by:

$$Y_{1,i} = \begin{cases} h_{11,i}X_{1,i} + h_{21,i}X_{2,i} + Z_{1,i} & 1 \leq i \leq l_h + l_d \\ h_{11,i}X_{1,i} + h_{21,i}X_{2,i} + h_{31,i}X_{3,i} + Z_{1,i} & l_h + l_d + 1 \leq i \leq l \end{cases} \quad (1a)$$

$$Y_{3,i} = \begin{cases} h_{13,i}X_{1,i} + Z_{3,i} & l_h + 1 \leq i \leq l_h + l_d, \\ 0 & \text{otherwise,} \end{cases} \quad (1b)$$

where $Z_{1,i}$ and $Z_{3,i}$ are noise samples observed at symbol interval i by D_1 and T_1 , respectively. These channel relations are used in deriving the DMT for the interference-limited user in the subsequent section.

III. DIVERSITY MULTIPLEXING TRADEOFF ANALYSIS

In this section, we introduce the DMT definitions, present some results used for performance comparison, and finally characterize the DMT performance of the proposed EH based DDF relaying protocol.

A. Preliminaries

The DMT captures the fundamental tradeoff between the data rate (through the multiplexing gain) and the reliability (through diversity gain) for quasi-static fading channels in the high-SNR

the contributions of this paper:

- Derived closed-form expressions for the DMTs of an interference-limited user using battery-assisted non-EH-based DDF and WEH-based DDF protocols. It is observed that adding a relay to the interference-limited system improves the diversity gain across all the multiplexing gains for both non-EH and WEH variants.
- Demonstrated that the DMT meets the performance upper-bound in low multiplexing gain regime for the non-EH-based DDF protocol
- For the WEH-based system, it is shown that the diversity performance degrades with the proportional increase in harvest duration. However, the numerical analysis revealed that the degree of degradation is minimal in the high multiplexing gain regime. This intriguing result is due to the dominance of interference over the harvest duration at high multiplexing gains.

The rest of the paper is organized as follows. The next section describes the system model and discusses the case where the intermediate relay nodes are powered by wireless energy harvesting. Section III details the analytic study of the DMT for both non-EH-based and WEH-based DDF protocols. Section IV presents the comparative study of proposed protocols. Furthermore, this section also discusses the impact of harvesting intervals on the achievable diversity gain for the WEH-based DDF protocol. Finally, Section V concludes the paper.

regime. The asymptotic definitions of multiplexing gain (r) and diversity gain (d) are given as follows [14]

$$d \triangleq -\lim_{\rho \rightarrow \infty} \frac{\log(P_E(\rho))}{\log(\rho)} \text{ and } r \triangleq \lim_{\rho \rightarrow \infty} \frac{R(\rho)}{\log(\rho)}, \quad (2)$$

where $P_E(\rho)$ is the error probability, ρ is the operating SNR ($\triangleq P_S/\sigma_{D_1}^2$), P_S is the transmit power, and $\sigma_{D_1}^2$ is the variance of the noise observed at the interference-limited user D_1 . In the proposed system, the sources $\{S_i\}_{i=1}^2$ transmit data at a rate of R_1 and R_2 bits per channel use (BPCU), respectively, during every symbol-interval in the codeword, and the associated multiplexing gains are denoted by r_1 and r_2 , respectively. For the performance comparison purposes, the DMTs of various reference schemes are presented in the subsequent subsection.

B. DMT of Reference Schemes:

The diversity gain achieved by three interference-free single-relay based reference schemes are presented. The first scheme is the genie-aided strategy where the relay is assumed to know the source information message a priori and thus provides an absolute upper bound (UB) for the achievable DMT, i.e., $d(r) - 2(1-r)$. The second baseline scheme is the DDF protocol [7, equation 14], and finally the third reference scheme is the EH based counterpart of second reference scheme (EHDDF) [9, equation 7]. Further, to elucidate the importance of incorporating a relay, the DMTs of a point-to-point (P2P) link (d_{P2P}) and an interference-limited user (d_{IL}) are given, respectively, as [15]:

$$d_{P2P}(r) = (1-r)^+, \quad d_{IL}(r) = \min\{(1-r)^+, 2(1-2r)^+\} \quad (3)$$

Note that the $d_{IL}(r)$ is also a lower-bound ($d_{LB}(r)$).

C. non-EH-based relay

The analysis starts with a traditional non-EH-based relay system whose DMT, in turn, provides an upper-bound for the WEH-based system. In this system model, the relay is powered by a fixed power source, thus, there is no energy harvesting phase. Therefore, it starts with the decoding phase and the number of symbols the relay listens to decode the source S_1 's data is equal to

$$l_d = \min \left\{ l, \frac{lR_1}{\log(1 + |h_{13}|^2 \rho)} \right\}, \quad (4)$$

and the high-SNR equivalent [7] of (4) is given by:

$$u_{13} = \left(1 - \frac{r_1}{f_1} \right)^+ \quad (5)$$

where $f_1 \triangleq l_d/l$ and u_{13} is the exponential order of $1/|h_{13}|^2$.

Since we are dealing with only one interference-limited user, i.e., D_1 , for notational convenience, we drop the subscripts i from D_i and T_i henceforth.

Achievable rate region at interference-limited user D: As discussed earlier, the interference-limited user D uses the JD to detect the desired signal from source S_1 [16]. Thus, the achievable rate region (R_1, R_2) at destination D of the proposed system using DDF protocol is given by

$$R_1 \leq f_1 \log(1 + P_S |h_{11}|^2) \quad (6a)$$

$$+ (1 - f_1) \log(1 + P_S |h_{11}|^2 + P_T |h_{31}|^2)$$

$$R_1 + R_2 \leq f_1 \log(1 + P_S |h_{11}|^2 + P_S |h_{21}|^2) \quad (6b)$$

$$+ (1 - f_1) \log(1 + P_S (|h_{11}|^2 + |h_{21}|^2) + P_T |h_{31}|^2),$$

where the relay transmit power, P_T , is considered to be equal to P_S . Inequalities in (6a) and (6b) represent the rate constraints related to the detection of message from source S_1 and the joint detection of messages from source S_1 and source S_2 , respectively. Note that, owing to the use of JD, the individual rate constraint related to the detection of interfering signal from source S_2 is absent. Thus, there are two kinds of outage regions denoted by $O_{\{1\}}$ and $O_{\{1,2\}}$, based on (6a) and (6b), respectively. In this work, we assume $R_1 = R_2 = R$ and $r_1 = r_2 = r$.

We partition the overall outage error event $\mathcal{E}$ into two error events $\mathcal{E}_1$ and $\mathcal{E}_2$ based on the outage regions $O_{\{1\}}$ and $O_{\{1,2\}}$, respectively, i.e., $\mathcal{E} = \mathcal{E}_1 \cup \mathcal{E}_2$. Hence, the achievable diversity gain for non-EH-based DDF protocol is given by

$$d_{non-EHDDF}(r) = \min\{d_{\mathcal{E}_1}(r), d_{\mathcal{E}_2}(r)\}, \quad (7)$$

and $d_{\mathcal{E}_1}(r)$ can be written as $P_{\mathcal{E}_1(r)} \doteq \rho^{-d_{\mathcal{E}_1(r)}}$, where $P_{\mathcal{E}_1(r)}$ is the error probability corresponding to outage event $\mathcal{E}_1(r)$ and $d_{\mathcal{E}_1(r)}$ is the diversity gain considering $P_{\mathcal{E}_1(r)}$ alone. Next, we focus on the computation of diversity gains based on these error events.

1) Error event related to individual rate ($\mathcal{E}_1$)

This problem is equivalent to the traditional single relay DDF protocol; thus the diversity gain for this category is given by [7, equation 14]

$$d_{\mathcal{E}_1}(r) = \begin{cases} 2(1-r), & 0 \leq r < \frac{1}{2} \\ \frac{1-r}{r}, & \frac{1}{2} \leq r \leq 1 \end{cases} \quad (8)$$

2) Error event related to sum-rate ($\mathcal{E}_2$)

The error probability corresponding to sum-rate $P_{\mathcal{E}_2}$ is upper-bounded by [7]

$$P_{\mathcal{E}_2|_{h_{ij}, i,j \in \{1,2,1,3,3,1\}}} \leq \left[1 + (|h_{11}|^2 + |h_{21}|^2) \frac{P_S}{2\sigma_D^2} \right]^{-l_d} \cdot \left[1 + (|h_{11}|^2 + |h_{31}|^2 + |h_{21}|^2) \frac{P_S}{2\sigma_D^2} \right]^{-(l-l_d)}, \quad (9)$$

and the corresponding diversity gain $d_{\mathcal{E}_2}$ is given by

$$d_{\mathcal{E}_2} \triangleq \inf_{O_{\mathcal{E}_2}^+} \{v_{11} + v_{21} + v_{31} + u_{13}\}, \quad (10)$$

where $\inf$ is the infimum, v_{ij} is the exponential order of $1/|h_{ij}|^2$ and $O_{\mathcal{E}_2}^+$ is the non-negative subset of $\mathbb{R}^5$ that satisfy the following constraints

$$f_1(1 - \min\{v_{11}, v_{21}\})^+ + (1 - f_1)(1 - \min\{v_{11}, v_{31}, v_{21}\})^+ \leq 2r \quad (11)$$

The diversity gain $d_{\mathcal{E}_2}$ in (10) can be expressed as

$$d_{\mathcal{E}_2}(r) = \inf_{f_1} (u_{13}(r, f_1) + \lambda_2(r, f_1)) \quad (12)$$

where $u_{13}(r, f_1)$ is given by (5) and $\lambda_2(r, f_1)$ is given as

$$\lambda_2(r, f_1) = \inf (v_{11} + v_{21} + v_{31}) \quad (13)$$

The function $\lambda_2(r, f_1)$ for this error event can be found by solving the following optimization problem:

$$\begin{aligned} \lambda_2(r, f_1) &= \inf (v_{11} + v_{21} + v_{31}) \\ \text{s.t. } f_1 \min\{v_{11}, v_{21}\} + (1-f_1) \min\{v_{11}, v_{21}, v_{31}\} &\geq (1-2r) \\ 0 &\leq v_{11}, v_{21}, v_{31} \leq 1 \end{aligned} \quad (14)$$

By using standard linear programming techniques, the solution to the above optimization problem can be written as

$$\lambda_2(r, f_1) = \begin{cases} 3(1-2r), & 0 \leq f_1 < \frac{2}{3} \\ 3 - \frac{2r}{1-f_1}, & \frac{2}{3} \leq f_1 \leq 1-2r \\ \frac{2(1-2r)}{f_1}, & 1-2r \leq f_1 \leq 1 \end{cases} \quad (15)$$

and

$$\lambda_2(r, f_1) = \begin{cases} 3(1-2r), & 0 \leq f_1 < \frac{2}{3} \\ \frac{2(1-2r)}{f_1}, & \frac{2}{3} \leq f_1 \leq 1 \end{cases} \quad (16)$$

Thus, using (5), (15), and (16),

$$d_{\mathcal{E}_2}(r) = 3(1-2r) \quad 0 \leq r < \frac{1}{2} \quad (17)$$

Finally, by using (8), and (17), the DMT for the non-EH relay based interference-limited user is given by

$$d_{non-EHDDF}(r) = \begin{cases} 2(1-r), & 0 \leq r < \frac{1}{4} \\ 3(1-2r), & \frac{1}{4} \leq r \leq \frac{1}{2} \\ 0, & \frac{1}{2} \leq r \leq 1 \end{cases} \quad (18)$$

The non-EH-based DDF achieves the optimal trade-off (the genie-aided upper bound) for lower multiplexing gains. In fact, in this multiplexing gain regime, the non-EHDDF behaves like a system with two transmit and one receive antennas with no degenerative effects of interference. Moreover, in this region, the dominant error event is related to individual rate constraint. However, as shown in (18), the diversity performance degrades in the high multiplexing gain regime. This result can be attributed to two factors. First, the detrimental effects of interference from an unintended user. Second, the limited co-operation from the relay due to the elongated decoding phase. These two effects manifest themselves in the sum-rate related error event.

D. WEH-based Relay

We now extend the analysis to the WEH-based relay system. In this model, the relay T is entirely powered by source S_1 's RF radiation. As shown in Fig. 1(b), during the first l_h symbols duration, relay T harvests the energy and is given by

$$E_T = \eta l_h |h_{13}|^2 P_S, \quad (19)$$

where $0 < \eta \leq 1$ is the RF-to-DC conversion efficiency. This entire harvested energy is used to re-transmit the source S_1 's data to the destination D_1 , thus the relay transmit power P_T is given by:

$$P_T = E_T / l_t \quad (20)$$

Therefore, the achievable rate region for WEH-based relay system can be obtained by replacing $f_1 = f_1 + \epsilon$ in (6). As in the case of the non-EH-based relay, the joint error event $\hat{\mathcal{E}}$ is written as a union of two error events $\hat{\mathcal{E}}_1$ and $\hat{\mathcal{E}}_2$ corresponding to an individual target rate of source S_1 and the overall sum-rate, respectively. Therefore, as in the case of non-EH-based DDF, the achievable diversity gain for WEH-based DDF protocol is given by

$$d_{WEH-DDF}(r) = \min\{d_{\hat{\mathcal{E}}_1}(r), d_{\hat{\mathcal{E}}_2}(r)\} \quad (21)$$

As in the case of non-EH relay based system, next, we present the analysis to find explicit expressions for diversity gains based on these error events.

1) Error Event related to individual rate ($\hat{\mathcal{E}}_1$)

This problem is equivalent to the WEH-based single relay DDF protocol, thus the diversity gain for this category is given by [9, equation 7]

$$d_{\hat{\mathcal{E}}_1}(r) = \begin{cases} 2 - \frac{9r}{4} \left(\frac{1-\epsilon}{1-(3\epsilon/2)} \right), & 0 \leq r \leq \left(\frac{4-5\epsilon}{6} \right) \\ \frac{1-r}{r+\epsilon}, & \left(\frac{4-5\epsilon}{6} \right) < r < (1-\epsilon) \\ (1-r), & (1-\epsilon) \leq r \leq 1 \end{cases} \quad (22)$$

2) Error Event related to sum-rate ($\hat{\mathcal{E}}_2$)

As in the case of non-EH-based system, the sum-rate related error probability $P_{\hat{\mathcal{E}}_2}$ is upper-bounded by

$$\begin{aligned} P_{\hat{\mathcal{E}}_2|_{h_{ij}, i,j \in \{11,21,13,31\}}} &\leq \left[1 + (|h_{11}|^2 + |h_{21}|^2) \frac{P_S}{2\sigma_D^2} \right]^{-(l_h+l_d)} \\ &\quad \left[1 + (|h_{11}|^2 + |h_{21}|^2) \frac{P_S}{2\sigma_D^2} + |h_{31}|^2 \frac{\eta l_h |h_{13}|^2 P_S}{2l_t \sigma_D^2} \right]^{-(l-l_h-l_d)} \end{aligned} \quad (23)$$

The diversity gain, $d_{\hat{\mathcal{E}}_2}$, for this category can be derived by solving the following optimization problem:

$$\begin{aligned} d_{\hat{\mathcal{E}}_2}(r, f) &= \inf (v_{11} + v_{21} + v_{31} + u_{13}) \\ \text{s.t. } f \min\{v_{11}, v_{21}\} &+ (1-f) \min\{v_{11}, v_{21}, v_{31} + u_{13}\} \geq (1-2r) \\ 0 &\leq v_{11}, v_{21}, v_{31}, u_{13} \leq 1, \end{aligned} \quad (24)$$

where $f = f_1 + \epsilon$. The solution is given in the following lemma

Lemma 1: The solution of the optimization problem defined in (24) is given by:

1) for $0 \leq \epsilon \leq \frac{1}{9}$

$$d_{\hat{\epsilon}_2}(r) = \begin{cases} \left(3 - \frac{98(4+\epsilon)r}{(8-5\epsilon)(8+9\epsilon)}\right)^+, & 0 \leq r \leq \frac{4}{7} + \frac{9\epsilon}{14} \\ \frac{2(1-2r)}{r+\epsilon}, & \frac{4}{7} + \frac{9\epsilon}{14} \leq r \leq \frac{1}{2} \end{cases} \quad (25)$$

2) and for $\frac{1}{9} \leq \epsilon \leq 1$

$$d_{\hat{\epsilon}_2}(r) = \left(3 - \frac{98(4+\epsilon)r}{(8-5\epsilon)(8+9\epsilon)}\right)^+ \quad (26)$$

Proof: Please refer to the Appendix A. ■

Finally, by using (22), (25), and (26), we get the DMT for the WEH-based DDF protocol as

1) for $0 \leq \epsilon \leq \frac{1}{9}$

$$d_{WEH-DDF}(r) = \begin{cases} 2 - 9r \left(\frac{(2-\epsilon)}{(4+\epsilon)(4-5\epsilon)} \right), & 0 \leq r \leq \frac{8}{31} + \frac{170\epsilon}{961} \\ \left(3 - \frac{98(4+\epsilon)r}{(8-5\epsilon)(8+9\epsilon)}\right)^+, & \frac{8}{31} + \frac{170\epsilon}{961} \leq r \leq \frac{8+9\epsilon}{14} \\ \frac{2(1-2r)}{r+\epsilon}, & \frac{8+9\epsilon}{14} \leq r \leq \frac{1}{2} \end{cases} \quad (27)$$

2) and for $\frac{1}{9} \leq \epsilon \leq 1$

$$d_{WEH-DDF}(r) = \begin{cases} 2 - 9r \left(\frac{(2-\epsilon)}{(4+\epsilon)(4-5\epsilon)} \right), & 0 \leq r \leq \frac{8}{31} + \frac{170\epsilon}{961} \\ \left(3 - \frac{98(4+\epsilon)r}{(8-5\epsilon)(8+9\epsilon)}\right)^+, & \frac{8}{31} + \frac{170\epsilon}{961} \leq r \leq \frac{1}{2} \end{cases} \quad (28)$$

The excellent diversity performance of the DDF protocol can also be observed for the WEH-based variant. As in the case of non-EH-based DDF, for lower multiplexing gains, the DMT performance depends on single user error event. On the other hand, the sum-rate error event is dominant in the high multiplexing gain regime. Due to the complicated nature of expressions, much of the insights are drawn using the performance plots in the subsequent section.

Fig. 2. DMT of interference-limited user using non-EH-based relay

Fig. 3. DMT of interference-limited user using WEH-based relay

IV. PROTOCOL COMPARISONS

In this section, the DMT of an interference-limited relay-aided user is compared with various reference schemes. Besides, the impact of energy harvesting duration on the achievable DMT for WEH-based system is also discussed.

A. non-EH-based relay-aided interference-limited User

The DMT for the non-EH-based relay-aided interference-limited user is shown in Fig. 2. As evident from the figure, the inclusion of relay improves the performance of interference-limited user across all the multiplexing gains compared to the interference-limited user without relay scenario (diversity lower bound (LB) in Fig. 2). Also, for multiplexing gains less than 0.25, the performance approaches that of genie-aided upper-bound. As shown in equation (18), the individual rate constraint is the limiting factor in the low multiplexing gain regime. However, for higher multiplexing gains, the resultant diversity gain hinges on the sum-rate constraint which in turn depends on the interference from source S_2 . Thus, the DMT diverges in this multiplexing gain regime and eventually offers no diversity advantage at multiplexing gain greater than $1/2$.

B. WEH-based relay-aided interference-limited User

Fig. 3 shows the DMT of a WEH-based relay-assisted interference-limited user for various fractions of energy harvesting durations (ϵ). It is observed that there is a performance degradation even for infinitesimal harvest duration $\epsilon (\approx 0)$ at lower multiplexing gains. This result arises from the resultant composite channel behavior owing to energy harvesting. Also, the EH based system exhibits degradation in performance with the increase in energy harvesting duration. This result is intuitive because the proportional increase in harvest duration results in the proportional decrease in cooperation phase. In the high multiplexing gain regime, as Fig. 3 indicates, WEH-based interference-limited user's performance approaches that of the non-EH-based counterpart. This result indicates that

the interference is the limiting factor rather than the energy harvesting duration at higher multiplexing gains.

V. CONCLUSION

In this work, the closed-form solutions for DMTs of traditional non-EH-based and WEH-based DDF protocols for the interference-limited user have been derived. These results showed that incorporating a relay improves the DMT of the interference-limited user. Surprisingly, for the proposed system, a WEH-based relay based system performs almost as good as a non-EH-based counterpart. The numerical analysis further revealed that the diversity gain drops to zero for multiplexing gains greater than 1/2 due to the dominant effect of interference, thus exploring solutions to improve the performance in this regime would be a promising future direction.

APPENDIX A

PROOF OF LEMMA 1

By setting $v_{11} = v_{21}$, and after further simplification,

$$\begin{aligned} d_{\hat{\mathcal{E}}_2}(r, f) &= \inf (2v_{11} + v_{31} + u_{13}) \\ \text{s.t. } f v_{11} + (1-f)v_{31} &\geq (1-2r) - (1-f) \left(1 - \frac{r}{f_1}\right)^+ \\ 0 &\leq v_{11}, v_{31}, u_{13} \leq 1 \end{aligned} \quad (29)$$

By using standard linear programming methods as in [9], we get

$$\begin{aligned} d_{\hat{\mathcal{E}}_2}(r) &= \inf_f \frac{2(1-2r)}{f} + \left(\frac{3f-2}{f}\right) \left(1 - \frac{r}{f-\epsilon}\right) \\ \text{s.t. } f &\geq \max \left\{ r + \epsilon, \frac{1+2\epsilon}{3} \right\} \end{aligned} \quad (30)$$

By taking the first derivative of (30) with respect to f and using the fact that $\sqrt{1-x} \approx 1 - \frac{x}{2}$ for $x \ll 1$, the candidate values of f which minimizes (30) can be found as

$$f = \max \left\{ \frac{4}{7} + \frac{9\epsilon}{14}, \frac{1+2\epsilon}{3}, r + \epsilon \right\} \quad (31)$$

By substituting the optimum value of f in (30), we get (25), and (26) and thus completes the proof. ■

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