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RF Energy Harvesting Based Relays: Non-orthogonal AF Vs Dynamic DF

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Abstract—A relay-based system, where the relay node is powered by radio frequency (RF) based energy harvesting (EH), has been considered. This work characterizes the diversity-multiplexing tradeoff (DMT) of non-orthogonal EH based amplify-and-forward (EH-NAF) protocol. Analysis of the protocols reveals that its DMT performance approaches that of non-EH based counterpart for smaller energy harvesting durations. Finally, EH-NAF is compared with EH based dynamic decode-and-forward (EH-DDF) protocol.

Index Terms—energy harvesting, relays, diversity-multiplexing tradeoff (DMT), amplify-and-forward (AF), dynamic decode and forward (DDF)

I. INTRODUCTION

Relaying has emerged as one of the widely used approaches to improve the quality of wireless links [1] owing to its ability to achieve distributed spatial diversity. In practice, the relay nodes are powered by batteries with a finite lifetime. This problem can be adequately addressed by employing energy harvesting (EH) based relays. Typically, the EH depends on the ambient sources such as solar, wind, and so on. However, the intermittent energy availability of such energy sources poses new challenges. This limitation can be resolved by powering the relay nodes with the source's radio frequency (RF) transmission [2].

Relaying protocols can be broadly classified into three categories: Amplify and Forward (AF) [3], Decode and Forward (DF) [4], and Compress and Forward (CF) [5]. In AF, the relay simply amplifies and retransmit the signal without decoding, and in DF schemes, the relay decodes the source's data before transmitting it to the destination, and finally in CF, the relay transmits a compressed version of its channel output to the destination, and the destination decodes by combining with its own output. The complexity of both CF and DF relays is significantly higher due to the intrinsic signal processing demands. Thus, in this work, we consider a non-orthogonal variant of EH based AF (EH-NAF) protocol.

Relaying can be used to increase either the achievable data rate or improve the reliability of the system. Traditionally, these effects are captured by spatial multiplexing gain and the diversity gain, respectively. Most of the existing literature related to EH based relaying [6]–[8] deals with either the maximum achievable rate or the outage probability. However, the more elegant performance metric which reveals the interplay between these two gains is the diversity-multiplexing

tradeoff (DMT) [9]. In [10], DMT has been characterized for RF EH based single relay channel using a variant of DDF protocol (EH-DDF). In [11], we extended the protocol for multiple relays. However, in practice, the implementation of DDF requires perfect timing synchronization along with the complex signal processing at the relay. Moreover, DDF requires rateless codes, which are more complicated than the codes used for simple DF schemes [12]. Therefore, in the low power applications, NAF protocols are preferred. Thus, this work focuses on the study of EH-NAF protocol in DMT perspective. The main contributions of this paper are the following:

- Closed-form expression for the DMT of EH based NAF protocol has been derived
- It is shown that the performance of EH-NAF protocol approaches that of non-EH based NAF when the fraction of harvest duration is less than $1/3$

The rest of the paper is organized as follows. Section II presents the overall system model and assumptions. Section III reviews the mathematical preliminaries. Section IV details the analytical derivation of the DMT for the EH-NAF scheme. Section V presents the numerical results from which various design insights are obtained. Finally, Section VI concludes the paper.

II. SYSTEM MODEL

This work considers a wireless system consisting of a source (S), a destination (D), and an EH-based relay (T) as shown in Fig. 2. All the fading coefficients $\{g_s, g_t, h\}$ are assumed to be independent and identically distributed (i.i.d) complex Gaussian random variables with zero mean and unit variance. We also assume that the channel is quasi-static over the entire codeword interval, l . As shown in the inset of Fig.2, the relay is of RF EH based with time-switching [13] among different modes of operation: Energy Harvesting (EH), Information Listening (IL) and re-transmission (TX). Relay harvests the energy during the first l_h symbol intervals, listens to the transmission for l_d symbol intervals, and finally, the information is amplified and then forwarded to the destination for the rest of the symbol intervals (l_t) as shown in Fig. 2. Note that the relay operates in half-duplex mode, i.e., it cannot receive and transmit simultaneously.

Fig. 1. EH based Non-orthogonal amplify-and-forward (EH-NAF) protocol

Fig. 2. System Model with EH based Relay Node

The EH based amplify-and-forward relaying is further illustrated in Fig. 1. The harvested energy E_T at the relay T , is given by

$$E_T = \eta l_h |h|^2 P_S, \quad (1)$$

where $0 \leq \eta \leq 1$ is the RF-to-DC conversion efficiency [14] and P_S is the average transmission power at S .

III. PROBLEM FORMULATION

The DMT essentially captures the high-SNR tradeoff of data rate and the reliability. Following [9], the asymptotic definitions of multiplexing gain (r) and diversity gain (d) are given as follows:

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

where $P_E(\rho)$ is the error probability of the ML decoder at the receiver, ρ is the operating SNR ($\triangleq P_S/\sigma_D^2$) and σ_D^2 is the variance of the noise observed at the destination D .

A. DMT of Reference Schemes:

For the comparison purposes, the diversity gain achieved by the non-EH based NAF protocol ($d_{NAF}(r)$) [15], EH based DDF and protocol ($d_{EH-DDF}(r)$) [11], and the DMT upper-bound ($d_{UB}(r)$) are given below:

$$d_{NAF}(r) = (1-r)^+ + (1-2r)^+ \quad (2)$$

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

$$d_{UB}(r) = 2(1-r) \quad (4)$$

B. DMT of EH-NAF

In the EH-NAF protocol, the source S transmits its message during the entire codeword duration at a rate of R BPCU. For $(l-l_h)/2$ symbol intervals, the relay listens to source transmission, and for the rest of $(l-l_h)/2$ symbol intervals, it transmits the scaled version of the source-to-relay signal to the destination using all the harvested energy. This work assumes that the relay uses all the accumulated energy for re-transmission. Thus, using (1), the transmission power of the relay P_T is given by

$$P_T = E_T/l_t, \quad \text{where } l_t = (l-l_h)/2 \quad (5)$$

We denote the relay repetition gain by b , and the information symbols during harvesting phase, listening phase and the re-transmission phase by x_h , x_1 , and x_2 respectively. Using this notation, the received signals at the destination can be written as:

$$\begin{aligned} y_h &= g_s x_h + n_{d,h} \\ y_1 &= g_s x_1 + n_{d,1} \\ y_2 &= g_s x_2 + b g_t (h x_1 + n_{t,1}) + n_{d,2} \end{aligned}$$

where $n_{d,h}$, $n_{d,1}$, and $n_{d,2}$ are the noise observed by the destination during the harvest phase, the transmission phase and the relaying phase respectively. Also, $n_{t,1}$ is the noise observed by the relay.

The repetition gain b is constrained by the quantum of energy harvested during l_h symbol intervals, thus using (1) and (5)

$$b \leq \sqrt{\frac{\eta l_h |h|^2 P_S}{(l-l_h)(|h|^2 E[|x_1|^2] + E[|n_{t,1}|^2])}} \quad (6)$$

$$\approx \sqrt{\frac{\eta l_h}{l-l_h}}. \quad (7)$$

The high SNR equivalent of the constraint on b is given by (7). The exponential order of b is equal to zero because (7) exclusively consists of scaling factors with no SNR related terms. Hence, the EH-NAF is equal to NAF [15] with the cooperation interval equal to $(l-l_h)/2$.

The pairwise error probability (PEP), P_{PE} , for the proposed EH-NAF system is upper-bounded by

$$P_{PE|g_s, g_t, h} \leq \left[1 + |g_s|^2 \frac{P_S}{2\sigma_D^2} \right]^{-l_h} \cdot \det \left(I_2 + \frac{1}{2} \Sigma_s \Sigma_n^{-1} \right)^{-(l-l_h)/2}, \quad (8)$$

where Σ_s and Σ_n are the covariance matrices of message and noise components at the destination:

$$\Sigma_s = \begin{bmatrix} |g_s|^2 & g_s g_t^* b^* h^* \\ g_s^* g_t b h & |g_s|^2 + |g_t|^2 |b h|^2 \end{bmatrix} E \quad (9)$$

$$\Sigma_n = \begin{bmatrix} \sigma_D^2 & 0 \\ 0 & \sigma_D^2 + |g_t|^2 |b|^2 \sigma_T^2 \end{bmatrix} \quad (10)$$

The noise term, $|g_t|^2|b|^2\sigma_T^2$, in (10) can be ignored in the asymptotic DMT analysis because it can be written as a non-positive power of SNR (ρ). By using (9) and (10), (8) can be rewritten as

$$P_{PE|g_s, g_t, h} \leq [1 + |g_s|^2 \rho]^{-l_h} \cdot [1 + |g_s|^2 \rho + (|g_s|^2 + |g_t|^2 |h|^2 |b|^2) \rho + |g_s|^4 \rho^2]^{-(l-l_h)/2} \quad (11)$$

Note that the scaling factors of SNR do not contribute towards the eventual DMT, thus omitted in (11). Defining v_s, v_t and u as the exponential orders [15] of $1/|g_s|^2$, $1/|g_t|^2$ and $1/|h|^2$, respectively, the outage region for EH-NAF can be defined as

$$O^+ = \{(v_s, v_t, u) \in \mathbb{R}^{3+} | \epsilon(1-v_s)^+ + \frac{1-\epsilon}{2} \max\{(1-(v_t+u))^+, 2(1-v_s)^+\} < r\} \quad (12)$$

where $\epsilon = l_h/l$. By denoting $v'_t = v_t + u$, considering the case where $0 \leq v_s, v'_t \leq 1$, and using the Laplace integration technique, the diversity gain can be evaluated as

$$d(r) = \inf_{(v_s, v'_t)} v_s + v'_t \quad \text{s.t. } \epsilon(1-v_s)^+ + \frac{1-\epsilon}{2} \max\{(1-v'_t)^+, 2(1-v_s)^+\} < r \quad (13a)$$

$$0 \leq v_s, v'_t \leq 1 \quad (13b)$$

The DMT of the proposed EH-NAF protocol can be characterized by solving the above optimization problem.

Theorem 1: The diversity gain achieved by the EH-NAF protocol is characterized by:

1) for $\epsilon \leq \frac{1}{3}$

$$d(r) = (1-r)^+ + (1-2r)^+ \quad (14)$$

2) and for $\epsilon > \frac{1}{3}$,

$$d(r) = \begin{cases} 1 + \left(1 - \frac{2r}{1-\epsilon}\right)^+, & 0 \leq r \leq \frac{1-\epsilon}{2} \\ \left(1 - \frac{r-\frac{1-\epsilon}{2}}{\epsilon}\right)^+, & \frac{1-\epsilon}{2} < r \leq \frac{1}{2} \\ (1-r), & \frac{1}{2} \leq r \leq 1 \end{cases} \quad (15)$$

Proof: Please refer to the Appendix A. ■

As evident from (2) and (14), for the fraction of energy harvest duration less than $1/3$, the achievable DMT with the EH-NAF protocol is same as that of non-EH based NAF scheme [15]. However, for $\epsilon \geq 1/3$, performance degrades due to the reduced cooperative phase.

IV. NUMERICAL RESULTS

In this section, we present the numerical results to illustrate the impact of the harvesting duration on the achievable diversity gain. These results are compared with the non-EH-based counterpart and also with the EH-based DDF.

Fig. 3 depicts the DMT performance of EH-NAF scheme for different energy harvest intervals. In this figure, the upper

Fig. 3. DMT for the EH-NAF Protocol

Fig. 4. DMT for EH-based Protocols

bound (UB) represents the scenario where the relay possesses a copy of source's data. As can be observed from the figure, the performance of EH-NAF protocol is same as that of non-EH based NAF for the harvesting fraction (ϵ) less than $1/3$. However, for $\epsilon > 1/3$, the performance deteriorates with the increase in harvest duration. This seemingly counter-intuitive result is due to the infinite SNR assumption in deriving the DMT. Hence, this result is applicable only to high SNR scenarios. Based on this observation, we conjecture that the non-EH based NAF achieves the maximum possible diversity gain even if the fraction of listening duration is less than $1/2$.

Fig. 4 shows the performance of both EH-DDF and EH-NAF schemes. As can be observed from the figure, EH-DDF outperforms the EH-NAF protocol across all the multiplexing gains for lower energy harvesting intervals. However, EH-NAF dominates over EH-DDF at higher ϵ . This result is consistent with the intuition. Because, in the case of DDF, the relay needs

to decode the data before it participates in the re-transmission. Thus, the probability of decoding failure at the relay increases with the increase in ϵ . However, in the case of NAF, the listening and the re-transmission intervals are equal. Hence, the effect of an increase in ϵ is ameliorated.

V. CONCLUSIONS

In this paper, the diversity-multiplexing-tradeoff is analyzed for energy harvesting based non-orthogonal amplify-and-forward (EH-NAF) protocol. Through the analysis, it is shown that the performance of EH-NAF approaches that of non-EH based counterpart for a fraction of energy harvesting duration (ϵ) less than $1/3$. However, its performance deteriorates with the increase in energy harvest duration for $\epsilon > 1/3$. It is also shown that the EH-DDF outperforms EH-NAF for lower ϵ , however, it underperforms EH-NAF at higher ϵ .

Finally, we envisage several avenues for future research. In particular, the study of these protocols in the purview of finite SNR is an interesting future direction.

APPENDIX A PROOF OF THEOREM 1

The optimization problem defined in (13) can be solved by identifying two disjoint constraint regions

$$1) \ 2(1 - v_s)^+ \geq (1 - v_t')^+$$

It is easy to see from (13) that for this category,

$$d(r) = (1 - r)^+ + (1 - 2r)^+. \quad (16)$$

$$2) \ 2(1 - v_s)^+ < (1 - v_t')^+$$

For this case, the (13) can be rewritten as

$$d(r) = \inf_{(v_s, v_t')} v_s + v_t' \quad (17a)$$

$$\text{s.t. } \epsilon(1 - v_s)^+ + \frac{1 - \epsilon}{2}(1 - v_t')^+ < r \quad (17a)$$

$$(1 - v_t')^+ \geq 2(1 - v_s)^+ \quad (17b)$$

$$0 \leq v_s, v_t' \leq 1 \quad (17c)$$

Based on ϵ , the constraint region for the above problem can be further subdivided into two regions as shown below

$$a) \ \epsilon \leq \frac{1}{3}$$

Fig. 5 and Fig. 6 depict the constraint regions for $\epsilon \leq \frac{1}{3}$. As can be seen from these figures, the achievable diversity gain for $\epsilon \leq \frac{1}{3}$ is given as

$$d(r) = \begin{cases} (1 - r)^+ + (1 - 2r)^+ & 0 \leq r \leq \frac{1}{2} \\ \frac{1}{2} & \frac{1}{2} \leq r \leq 1 \end{cases} \quad (18)$$

$$b) \ \epsilon > \frac{1}{3}$$

Similar to the earlier case, Fig. 7 and Fig. 8 illustrate the constraint regions for $\epsilon > \frac{1}{3}$. Referring

Fig. 5. Outage region: $\epsilon \leq \frac{1}{3}, 0 \leq r \leq \frac{1}{2}$

Fig. 6. Outage region: $\epsilon \leq \frac{1}{3}, \frac{1}{2} \leq r \leq 1$

to these figures, the achievable diversity gain for $\epsilon > \frac{1}{3}$ can be written as

$$d(r) = \begin{cases} 1 + \left(1 - \frac{2r}{1 - \epsilon}\right)^+ & 0 \leq r \leq \frac{1 - \epsilon}{2} \\ \left(1 - \frac{r - \frac{1 - \epsilon}{2}}{\epsilon}\right)^+ & \frac{1 - \epsilon}{2} < r \leq \frac{1}{2} \\ \frac{1}{2} & \frac{1}{2} \leq r \leq 1 \end{cases} \quad (19)$$

Now, (16), (18) and (19), result in (15) and the proof is complete.

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Fig. 7. Outage region: $\epsilon > \frac{1}{3}$, $0 \leq r \leq \frac{1}{2}$

Fig. 8. Outage region: $\epsilon > \frac{1}{3}$, $\frac{1}{2} \leq r \leq 1$

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