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On the DMT of RF energy harvesting based dynamic decode-and-forward relaying

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***Abstract*—A multiple relay-based system, where all the relay nodes powered by radio frequency (RF) based energy harvesting (EH), is considered. Assuming independent quasi-static Rayleigh fading channels across all links, characterized the diversity-multiplexing tradeoff (DMT) for EH based dynamic decode-and-forward protocol (EH-DDF). It is shown that the achievable diversity gain of EH-DDF improves with the reduction in the energy harvesting intervals. However, it is observed that the performance difference exists between classical dynamic decode-and-forward (DDF) and EH-DDF even for infinitesimal harvest duration in lower multiplexing gain region.**

***Index Terms*—energy harvesting, relays, diversity multiplexing trade-off (DMT), dynamic decode and forward (DDF)**

I. Introduction

Usage of relay nodes is an elegant option to improve the performance in slow fading environment without equipping any additional antennas [1]. Typically the relay nodes are powered by batteries with a limited lifetime. In recent years, there has been a surge of interest in *energy harvesting* (EH) which can elegantly alleviate this long-standing energy constraint. In particular, radio frequency (RF) energy harvesting gained prominence in prolonging the lifetime of such networks. In the case of non-EH-based relaying, the diversity gain improves with the increase in the number of relay nodes [1]. Inspired by this result, we investigate whether the similar improvement can be achieved even with EH-based relaying.

To the best of our knowledge, only [2] has attempted the analysis related to diversity-multiplexing tradeoff (DMT) of EH based DDF protocol for a single relay based system. Most of the state-of-the-art [3]–[5] considered either the outage probability or the maximum throughput as the performance metric. In our work, we specifically used the in-band RF EH [6] and the *harvest-use* [7] power management in deriving the closed-form DMT expression for EH based dynamic decode-and-forward protocol (EH-DDF). Unlike the standard dynamic decode-and-forward (DDF) protocol [1], this problem has to deal with a product channel. To that end, the following are the significant contributions of this letter:

- Derived the closed-form expression for the DMT of multi-relay system with EH-DDF protocol
- Concluded that the performance difference with reference to classical non-EH-based DDF cannot be eliminated by reducing the energy harvesting interval.

II. System Model

This work considers a wireless network consisting of a source (S), a destination (D), and N EH-based relays as shown

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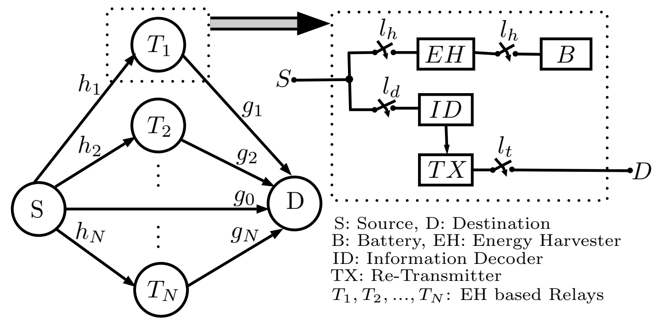

Fig. 1. System Model with N Relay Nodes

in Fig. 1. In this letter, the fading coefficients $\{g_i\}_{i=0}^N$ and $\{h_i\}_{i=1}^N$ are assumed to be independent and identically distributed complex Gaussian random variables with zero mean and unit variance. Extension of the analysis to independent and non-identically distributed channels is left for the future work. We also assume that the channel is constant over the entire codeword interval, l. As shown in the inset of Fig.1, all the relays are of RF EH based with time-switching [8] among different modes of operation: Energy Harvesting (EH), Information Decoding (ID) and re-transmission (TX). Relay harvests the energy during the first l_h symbol intervals, switches to information decoding phase for l_d symbol intervals, and finally after successful decoding, the information is forwarded to the destination for the rest of the symbol intervals (l_t) as shown in Fig. 1.

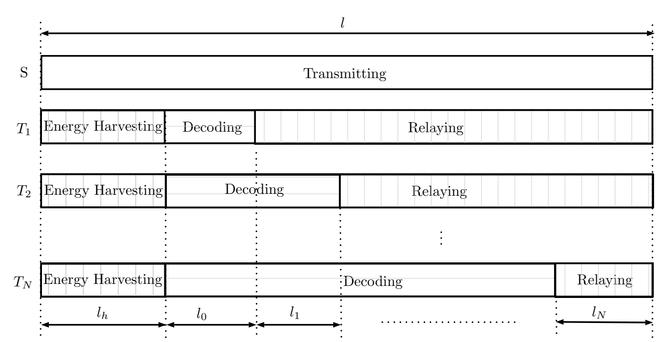

Fig. 2. EH based Dynamic Decode-and-Forward protocol

The dynamic relaying is further illustrated in Fig. 2. In the considered EH-DDF protocol, S transmits data at a rate of R bits per channel use (BPCU) during every codeword. The harvested energy E_i at the relay T_i, $i \in \{1, ..., N\}$, is given by

$$E_i = \eta l_h |h_i|^2 P_S, \tag{1}$$

where $0 < \eta \leq 1$ is the RF-to-DC conversion efficiency [7] and P_S is the average transmission power at S. All the relays, $\{T_p\}_{p=1}^{N}$, harvest the energy during the first l_h symbol intervals. Also, the number of symbol intervals that the relay T_p, $p \in \{1,...,N\}$, has to wait until it receives enough mutual information, lR, to decode the source message is given by

$$\sum_{j=0}^{p-1} l_j = \min\left\{ l - l_h, \left\lceil \frac{lR}{\log(1+|h_p|^2 \frac{P_S}{\sigma_p^2})} \right\rceil \right\}. \quad (2)$$

Where $\lceil . \rceil$ is the ceiling function, l_j is the number of symbol intervals in the codeword during which j relays are re-transmitting the source message, and σ_p^2 denote the variance of the noise observed at the relay T_p, $p \in \{1,...,N\}$.

After the decoding phase, the relay T_p forwards the source information during the remaining symbol intervals using all the harvested energy E_p for re-transmission. Thus, using (1), the transmission power P_p is given by

$$P_p = \frac{E_p}{l_t}, \quad \text{where} \quad l_t = l - (l_h + \sum_{j=0}^{p-1} l_j). \quad (3)$$

III. Achievable DMT

DMT is used to characterize the tradeoff between the reliability (via diversity gain, d) and the throughput (via multiplexing gain, r) of a protocol [9]. A diversity gain $d(r)$ is achieved at multiplexing gain r if $d(r) \triangleq -\lim_{\rho\to\infty}(\log(P_E(\rho))/\log(\rho))$ and $r \triangleq \lim_{\rho\to\infty}(R(\rho)/\log(\rho))$, where $P_E(\rho)$ is the error probability, 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. As in [1], the pairwise error probability (PEP), P_{PE}, for the EH-DDF based multi-relay system shown in Fig. 1 is upper-bounded by

$$P_{PE|g_j,h_j} \leq \left[1 + |g_0|^2 \frac{P_S}{2\sigma_D^2}\right]^{-(l_h+l_0)} \cdot \prod_{j=1}^{N} \left[1 + |g_0|^2 \frac{P_S}{2\sigma_D^2} + \left(\sum_{i=1}^{j} |g_i|^2 \frac{P_i}{2\sigma_D^2}\right)\right]^{-l_j} \quad (4)$$

Using (3), (4) can be written as

$$P_{PE|g_j,h_j} \leq \left[1 + |g_0|^2 \frac{P_S}{2\sigma_D^2}\right]^{-(l_h+l_0)} \cdot \quad (5)$$
$$\prod_{j=1}^{N} \left[1 + |g_0|^2 \frac{P_S}{2\sigma_D^2} + \left(\sum_{i=1}^{j} \frac{l_h \eta |h_i|^2}{l - (l_h + \sum_{k=0}^{j-1} l_k)} |g_i|^2\right) \frac{P_S}{2\sigma_D^2}\right]^{-l_j}$$

In the case of traditional DDF protocol, the RHS of (5) contains only the channel gains related to relay-to-destination link, $\{g_i\}_0^N$. However, in the case of EH-DDF, the channel to be considered is a product of $|h_i|^2$ and $|g_i|^2$. The resultant composite channel behavior determines the achievable DMT of EH-DDF protocol. Defining v_j and u_j as the exponential orders [1] of $1/|g_j|^2$ and $1/|h_j|^2$, respectively, we have

$$P_{PE|v_j,u_j} \dot{\leq} \rho^{-(l_h+l_0)(1-v_0)^+ + \sum_{j=1}^{N} -l_j(1-\min\{v_0, v_1+u_1 ..., v_j+u_j\})^+},$$

where $(x)^+ \triangleq \max\{0, x\}$. As one can notice, the term related to energy harvesting interval l_h in (5) appears as a scaling factor and hence disappear in the exponential based asymptotic analysis.

Suppose that the source uses a Gaussian codebook with a rate $R = r\log(\rho)$, or equivalently the total number of codewords equal to ρ^{rl}, then the conditional error probability, P_E can be derived as

$$P_{E|v_j,u_j} \dot{\leq} \rho^{-l[\frac{(l_h+l_0)}{l}(1-v_0)^+ + \sum_{j=1}^{N} \frac{l_j}{l}(1-\min\{v_0, v_1+u_1 ..., v_j+u_j\})^+ - r]}.$$

The above error event occurs if $\{v_i\}_{i=0}^{N}$ and $\{u_i\}_{i=1}^{N}$ satisfy the following constraint

$$\frac{l_h + l_0}{l}\min\{1, v_0\} + \sum_{j=1}^{N} \frac{l_j}{l} \min\{1, v_0, v_1+u_1, ..., v_j+u_j\} \geq 1 - r.$$

Using Laplace integration technique as in [1], diversity gain related to the above error event can be evaluated as

$$\begin{aligned} d(r) &= \inf_{(v_i, u_i, \{f_i\}_0^N)} v_0 + \sum_{i=1}^{N}(v_i + u_i) \\ &\text{s.t. } \epsilon(1-v_0)^+ + \sum_{i=0}^{N} f_i(1 - \min\{v_0, v_1+u_1, ...v_i+u_i\})^+ \leq r \\ &v_i \geq 0,\ u_i = \left(1 - \frac{r}{\sum_{k=0}^{i-1} f_k}\right), \end{aligned} \quad (6)$$

where u_i is the exponential order equivalent of (2), $f_j \triangleq l_j/l$, and the $\epsilon(= l_h/l)$ is the fraction of symbol intervals during which the energy is harvested by relay nodes. The solution to the above optimization problem gives the DMT for the proposed protocol as shown in Theorem 1.

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

1) for the single relay ($N = 1$)

$$d(r) = \begin{cases} 2 - \frac{9r}{4}\left(\frac{1-\epsilon}{1-(3\epsilon/2)}\right), & 0 \leq r \leq (\frac{2}{3} - \frac{5\epsilon}{6}) \\ \frac{1-r}{r+\epsilon}, & (\frac{2}{3} - \frac{5\epsilon}{6}) < r < (1-\epsilon) \\ 1 - r, & (1-\epsilon) \leq r \leq 1 \end{cases} \quad (7)$$

2) and for multiple relays ($N > 1$),

$$d(r) = \begin{cases} \frac{2(1-r)}{1+\epsilon} + \left((N+1) - \frac{2}{1+\epsilon}\right)\left(1 - \frac{2r}{1-\epsilon}\right), & 0 \leq r \leq (\frac{1-\epsilon}{2}) \\ \frac{1-r}{r+\epsilon}, & (\frac{1-\epsilon}{2}) < r < (1-\epsilon) \\ 1 - r, & (1-\epsilon) \leq r \leq 1 \end{cases} \quad (8)$$

Proof: Please refer to the Appendix A. ■

The DMT of the DDF protocol characterized by [1, Theorem 6] uniformly dominates the considered EH-DDF protocol. It is intuitive because the relays in EH-DDF assist the source for less duration compared to the case in DDF. However, the surprising revelation is that this performance difference cannot be removed by reducing the harvest interval as detailed in the subsequent section.

IV. Numerical Results

In this section, the impact of the harvesting intervals and the effect of the number of relays on the achievable diversity gain is investigated, and it is compared with the non-EH-based DDF protocol. The maximum achievable DMTs for the proposed EH-DDF protocol for the single relay ($N = 1$) and for multiple

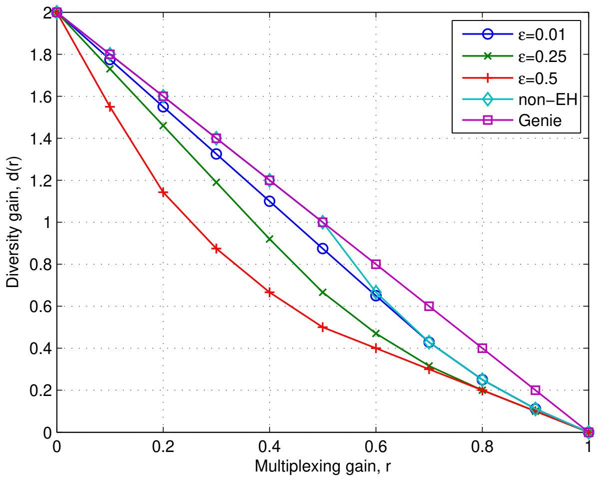

Fig. 3. DMT for the EH-DDF Protocol with one relay

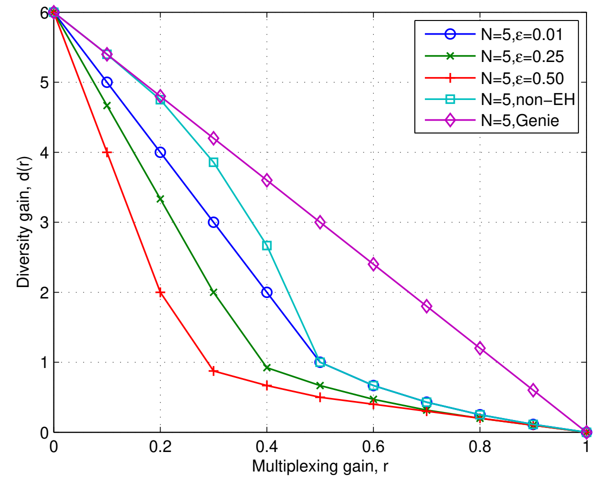

Fig. 4. DMT for the EH-DDF Protocol with N=5

relays ($N > 1$) are deduced by solving (7) and (8) for $\epsilon \longrightarrow 0$ respectively. For $N = 1$, the resultant diversity gain is given by

$$d(r) = \begin{cases} 2 - \frac{9r}{4}, & 0 \le r \le \frac{2}{3} \\ \frac{1-r}{r}, & \frac{2}{3} < r < 1. \end{cases} \quad (9)$$

and for multi-relay based system ($N > 1$),

$$d(r) = \begin{cases} 2(1-r) + (N-1)(1-2r), & 0 \le r \le \frac{1}{2} \\ \frac{1-r}{r}, & \frac{1}{2} < r \le 1 \end{cases} \quad (10)$$

The DMT for the single relay based system is shown in Fig. 3. In this figure, the genie-aided strategy corresponds to the case where the relay is assumed to know the information message a priori, is the upper bound on achievable DMT for the non-EH system. There is a performance difference between EH-DDF and DDF protocols of [1] even for the infinitesimal harvest duration ($\epsilon \approx 0$). This result is due to the composite channel behavior of a proposed system. Also, the performance of EH-DDF deteriorates with increase in ϵ because the relay could forward the source message for a shorter fraction of the codeword. As evident from the Fig. 3, the DMT curve for $\epsilon \approx 0$ coincide with that of non-EH based DDF for $r > 2/3$. Fig. 4 shows the DMT performance for $N = 5$. Similar observations related to performance penalty can be made for this system as well. However, in this case, the threshold at which the performance meets the DDF protocol is at $r \approx 1/2$. Finally, Fig. 5 illustrates the DMT for different values of N. In the case of non-EH DDF, there is no performance difference with respect to genie-aided protocol for multiplexing gain (r) lower than $1/(N+1)$, on the other hand the DMT of EH-DDF protocol diverges from genie-aided strategy right from $r = 0$. This behavior is again due to the product channel resulted out of EH-DDF.

V. Conclusions

In this work, we have derived the diversity-multiplexing-tradeoff of RF energy harvesting based multiple relay channel. It is observed that the proposed method of incorporating the energy harvesting mechanism radically changes the channel behavior and thus results in inferior performance. It is shown

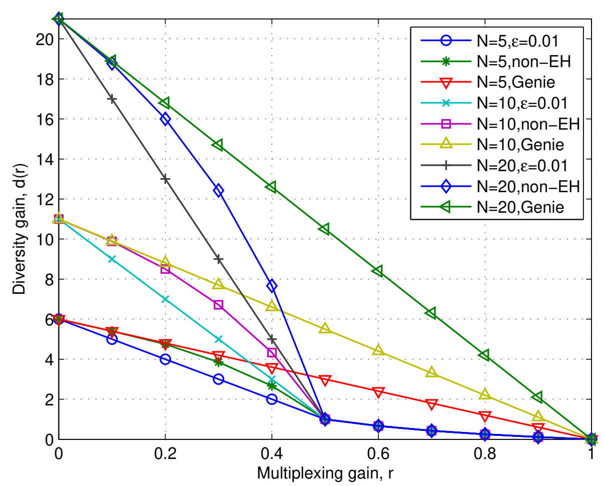

Fig. 5. DMT for the EH-DDF Protocol with N = 5, 10, and 20

that the performance of the proposed EH-DDF protocol improves with the reduction in the proportion of energy harvesting interval. Finally, it is concluded that the performance difference between non-EH based DDF and EH-DDF exists even for infinitesimal harvest duration.

Appendix A
Proof of Theorem 1

We only need to consider the case where $1 \ge v_0 \ge (v_1 + u_1) \ge \ldots \ge (v_j + u_j), \forall j \le N$ [1]. Hence, we can restrict the solution space for the problem defined in (6) as follows,

$$\begin{aligned} d(r) = & \inf_{(v_i, u_i, \{f_i\}_0^N)} v_0 + \sum_{i=1}^{N} (v_i + u_i) \\ \text{s.t. } & \epsilon v_0 + \sum_{i=0}^{N} f_i v_i \ge 1 - r - \sum_{i=1}^{N} f_i u_i \\ & 1 \ge v_0 \ge (v_1 + u_1) \ge \ldots \ge (v_N + u_N) \ge 0 \\ & v_i \ge 0,\ u_i = \left(1 - \frac{r}{\sum_{k=0}^{i-1} f_k}\right)^+,\ i \in \{1, \ldots, N\} \end{aligned} \quad (11)$$

For $v_0 \leq 1$, using the constraint set of (11), f_0 is lower bounded as follows

$$f_0 \geq \frac{1-r-\sum_{i=1}^{N} f_i(v_i+u_i)}{v_0} - \epsilon \geq 1-r-\sum_{i=1}^{N} f_i u_i - \epsilon \geq \frac{1-\epsilon}{2},$$

also, there is one more constraint for f_0 based on $u_i \geq 0$, i.e., $f_0 \geq r$. By defining $x_i \triangleq (i+1)(v_i - v_{i+1})$, $\{i=0,\ldots,N-1\}$, $x_N \triangleq (N+1)v_N$, it can be easily seen that

$$\sum_{i=0}^{N} v_i = \sum_{i=0}^{N} x_i,\ \epsilon v_0 + \sum_{i=0}^{N} f_i v_i = \sum_{i=0}^{N} \frac{\epsilon + \sum_{k=0}^{i} f_k}{i+1} x_i \tag{12}$$

Using (12), (11) can be rewritten in terms of x_i as

$$\begin{aligned} d(r) = & \inf_{(x_i, u_i, \{f_i\}_0^N)} x_0 + \sum_{i=1}^{N} (x_i + u_i) \\ \text{s.t.} & \sum_{i=0}^{N} \frac{\epsilon + \sum_{k=0}^{i} f_k}{i+1} x_i \geq \left(1 - r - \sum_{i=1}^{N} f_i u_i\right) \\ & x_i \geq 0, \quad u_i = 1 - \frac{r}{\sum_{k=0}^{i-1} f_k},\ i \in \{1,\ldots,N\} \\ & f_0 \geq \max\left\{\frac{1-\epsilon}{2},\ r\right\} \end{aligned} \tag{13}$$

By using the standard linear programming technique, (13) can be rewritten as

$$\inf_{(x_i,u_i,\{f_i\}_0^N)} x_0 + \sum_{i=1}^{N}(x_i+u_i) = \frac{(p+1)\left(1-r-\sum_{i=1}^{N} f_i u_i\right)}{\epsilon + \sum_{k=0}^{p} f_k} + \sum_{i=1}^{N} u_i \tag{14}$$

$$\text{where } p = \arg\max_{0\leq j\leq N} \left\{\frac{\epsilon + \sum_{k=0}^{j} f_k}{j+1}\right\},\ f_0 \geq \max\left\{\frac{1-\epsilon}{2},\ r\right\},$$

$$\text{and } \left(\epsilon + \sum_{k=0}^{p} f_k\right) \geq (p+1)\left(1-r-\sum_{i=1}^{N} f_i u_i\right)$$

Using (14), we can characterize the DMT as:

$$\begin{aligned} d(r) = & \inf_{(p,u_i,\{f_i\}_{i=0}^N)} \frac{(p+1)(1-r)}{\epsilon + \sum_{k=0}^{p} f_k} + \sum_{i=1}^{N}\left(1 - \frac{(p+1) f_i}{\epsilon + \sum_{k=0}^{p} f_k}\right) u_i \\ \text{s.t.} & \ u_i = \left(1 - \frac{r}{\sum_{k=0}^{i-1} f_k}\right),\ i \in \{1,\ldots,N\} \\ & f_0 \geq \max\left\{\frac{1-\epsilon}{2},\ r\right\} \end{aligned} \tag{15}$$

We can prove that the objective function of the optimization problem in (15) is an increasing function of p by showing that its partial derivative with respect to p is positive for all the values of $\{f_i\}_{i=0}^N$, i.e.,

$$\frac{\partial d}{\partial p} = \frac{(1-r)}{\epsilon + \sum_{k=0}^{p} f_k} - \frac{1}{\epsilon + \sum_{k=0}^{p} f_k} \sum_{i=1}^{N} f_i u_i > 0 \tag{16}$$

$$\because (1-r) > (1-f) u_N \geq \sum_{i=1}^{N} f_i u_i$$

Hence, the infimum of (15) with reference to p occurs at $p = 0$ and now (15) can be rewritten as

$$\begin{aligned} d(r) = & \inf_{(\{f_i\}_{i=0}^N)} \frac{(1-r)}{\epsilon + f_0} + \sum_{i=1}^{N}\left(1 - \frac{f_i}{\epsilon + f_0}\right)\left(1 - \frac{r}{\sum_{k=0}^{i-1} f_k}\right) \\ & \text{s.t. } f_0 \geq \max\left\{\frac{1-\epsilon}{2},\ r\right\} \end{aligned} \tag{17}$$

Lemma 1: The objective function of (17) is an increasing function of f_i, $1 \leq i \leq (N-1)$ for given f_0 and ϵ.

Proof: For $N = 2$, The objective function of (17) can be written as

$$\begin{aligned} d(r, f_0, f_1, f_2) = & \frac{1-r}{\epsilon + f_0} + \left(1 - \frac{f_1}{\epsilon + f_0}\right)\left(1 - \frac{r}{f_0}\right) \\ & + \left(1 - \frac{f_2}{\epsilon + f_0}\right)\left(1 - \frac{r}{f_0 + f_1}\right). \end{aligned} \tag{18}$$

If f_1 increases to $f_1 + \delta$, then f_2 decreases to $f_2 - \delta$ for fixed f_0 and ϵ ($\because \epsilon + f_0 + f_1 + f_2 = 1$), hence

$$\begin{aligned} d(r, f_0, f_1+\delta, f_2-\delta) = & \frac{1-r}{\epsilon + f_0} + \left(1 - \frac{f_1+\delta}{\epsilon + f_0}\right)\left(1 - \frac{r}{f_0}\right) \\ & + \left(1 - \frac{f_2-\delta}{\epsilon + f_0}\right)\left(1 - \frac{r}{f_0 + f_1 + \delta}\right). \end{aligned} \tag{19}$$

By subtracting (18) from (19), we get

$$\begin{aligned} \Delta d = & \left(\frac{\delta}{\epsilon + f_0}\right)\left(\frac{r}{f_0} - \frac{r}{f_0 + f_1 + \delta}\right) \\ & + \left(1 - \frac{f_2}{\epsilon + f_0}\right)\left(\frac{r}{f_0 + f_1} - \frac{r}{f_0 + f_1 + \delta}\right) > 0 \quad \text{for } \delta > 0. \end{aligned} \tag{20}$$

Hence, $d(r, f_0, f_1, f_2)$ is an increasing function of f_1 for a given f_0 and ϵ. By the principle of induction, we can conclude that (17) is an increasing function of $(f_1, \ldots, f_{N-1})$ for a given f_0 and ϵ. This completes the proof. ■

By substituting the optimum values of $\{f_i\}_{i=1}^{N-1}$ based on Lemma (1), and by also replacing f_N with $(1 - f_0 - \epsilon)$ in (17), we get

$$\begin{aligned} d(r) = & \inf_{(f_0)} \frac{1-r}{f_0 + \epsilon} + \left(\frac{(N+1)(f_0+\epsilon) - 1}{f_0 + \epsilon}\right)\left(1 - \frac{r}{f_0}\right) \\ & \text{s.t. } f_0 \geq \max\left\{\frac{1-\epsilon}{2},\ r\right\} \end{aligned} \tag{21}$$

By taking the first derivative of (21) with respect to f_0 and using the fact that $\sqrt{1-x} \approx 1 - \frac{x}{2}$ for $x \ll 1$, the candidate values of f_0 which minimizes (21) can be found as

$$f_0 = \max\left\{\frac{2}{N+2} - \frac{(2N+3)\epsilon}{2N+4},\ \frac{1-\epsilon}{2},\ r\right\} \tag{22}$$

For $N = 1$, the first term on the right hand side (RHS) of (22) is the optimal value for f_0. While for $N > 1$, the second term on the RHS of (22) is the optimal value for f_0. Using these optimal values, the first two diversity order terms in (7) and (8) can be obtained. Finally, when $f_0 \geq 1 - \epsilon$, none of the relays participate in the retransmission phase, hence, the diversity gain is equal to that of a point-to-point link $(1-r)$. Hence, proved.

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