Dynamic Harvest-and-Forward: New Cooperative Diversity with RF Energy Harvesting

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***Abstract*—In this paper, we propose a new cooperative diversity technique with radio frequency (RF) energy harvesting named *dynamic harvest-and-forward* (DHF) cooperation. This cooperation enables to obtain diversity gain with consuming neither extra energy nor extra bandwidth by exploiting the relay's proximity advantage over the destination. We analyze the proposed approach in terms of outage probability and show that the DHF cooperation can achieve the diversity order of two (full diversity) in typical three node cooperation scenario. We also investigate the effect of geometrical arrangement and show that the advantageous region of DHF cooperation over the direct transmission without the energy harvesting relay.**

I. Introduction

Typical wireless channels suffer from multipath fading and shadowing which significantly reduce communication capacity for a given average transmission power and hinder reliable transmission. Although an effective option is using multiple antennas to obtain spatial diversity gain [1]–[3], it is practically difficult to equip multiple antennas in some applications such as sensor networks because of the size, complexity, and cost. In order to overcome this issue, another concept has been proposed in the literature; when the source cannot reliably communicate with the destination, other available nodes can temporarily work as relays in order to support the communication by expending their own energies regularly supplied by pre-charged batteries, which is called *cooperative diversity* and allows nodes to enjoy spatial diversity gain without equipping additional antennas [4]–[8]. Cooperative diversity inherently consumes the battery of users to support some users having with small channel capacities. Thus, it is important to reduce the energy consumption used to forward the signals. To this end, amplify-and-forward (AF) relaying has been actively studied in the literature because of the simple functionality. In the AF relaying, the relay only re-transmits the scaled or amplified version of the received signals and thus neither decoding nor demodulation is needed. However, when power amplifier (PA) efficiency is considered, decode-and-forward (DF) relaying may be beneficial since the AF relaying has to transmit noisy signals [9]. Considering this PA issue, the energy-efficient relaying has been studied in [10]. The cooperation yet consumes additional energy from pre-charged battery, which may results in shorter network life since more nodes drain their batteries at the same time.

A remedy for this crucial battery issue is the use of energy harvesting [11]. Energy harvesting technologies enable devices to harness energy from ambient sources such as solar, vibration, themoelectric effects, and so on. Since this might be an ultimate solution of the crucial energy constraint, it has gained much attention from researchers. Especially, radio frequency (RF) energy harvesting does not depend on availability of ambient energy sources where ambient RF radiation is captured by the receiver antennas and converted into a direct current (DC) voltage through appropriate circuits such as rectennas [12], [13]. Therefore, this RF energy transfer is considered as one of the most attractive candidate technologies to realize self-sustaining networks.

The performance of cooperative communication with multiple energy harvesting relays has been studied and the advantage of using relays was shown in [14] where energies harvested by the relays were assumed to be a stationary and ergodic process with a constant mean. However, the source of energy deeply depends on the ambient environment and thus the energy may not be generated for a long period. In [15], wireless energy transfer such as RF energy harvesting has been considered in scenarios with cooperative communications besides conventional energy harvesting and it was shown that the outage probability performance can be improved by harvesting energy from ambient RF signals. Furthermore, one-hop AF relaying with practical finite pre-charged battery model has been studied in [16] where only RF energy harvesting was assumed as the source of energy. Although these seminal works showed the advantage of energy harvesting, the relay still utilizes the pre-charged battery and consumes its own energy.

Wireless-powered cooperative communications have been investigated quite recently in [17], [18]. In [17], the dynamic wireless power transfer and information transmission in the typical three node network where all the transmitters are activated on the fly by highly efficient wireless power transfer from the base station (BS) to transmitters in order to send the information from the transmitters to the BS. Also, in [18], throughput and ergodic capacity of one-hop DF relaying with RF energy harvesting has been investigated where the relay harvests the energy from the source's signals. These wireless-powered cooperative protocols are composed of the following three phases: 1) RF energy harvesting, 2) source-to-relay transmission, and 3) cooperative phase. The latter two phases have the same length of duration as similar to conventional two-phase cooperative protocols [4]–[8]. However, conventional two-phase approaches require extra orthogonal channel to meet a half duplex constraint and reduce an overall bandwidth efficiency of the network.

Regularly, cooperative communications become beneficial when the relay is placed nearby the source since the channel quality between the source and relay defines whether the relay can successfully decode the source's information or not. Also, from the energy harvesting point of view, if the relay is close to the source, the relay can obtain the sufficient energy from the source's transmission in a short time. From these observations, *dynamic decode-and-forward* (DDF) [19]–[22] cooperation is more appropriate for energy harvesting cooperation. In this protocol, if the receivers (i.e., relay and destination) have a knowledge of network configuration, the relay can dynamically superimpose cooperating signals on the original signal from the source using the same channel upon successfully decoding the source's information. As a result, the destination can achieve the diversity gain without extra channel resources.

In this paper, we propose a new cooperative diversity technique based on DDF cooperation with RF energy harvesting named *dynamic harvest-and-forward* (DHF) cooperation. This cooperation allows us to obtain diversity gain with consuming neither extra energy nor extra bandwidth by exploiting the relay's proximity advantage over the destination. We analyze this approach in terms of outage probability and show that the DHF cooperation can achieve the diversity order of two (full diversity) in three node cooperation scenario.

The paper is organized as follows. Section II describes the system model including geometrical relationship between transmitters which is treated throughout the paper. Section III explains the proposed DHF cooperative protocol and we derive outage probability of DHF cooperation in Section IV. Numerical results in Section V show the advantage of proposed approach and clarify the advantageous region of RF energy harvesting relay without consuming extra energy and bandwidth. Finally, Section VI concludes this work.

II. System Model

Figure 1 illustrates the geometrical model considered throughout the paper. The network is composed of three nodes: source (S), relay (R) and destination (D). Three nodes are assumed to be located in two-dimensional plane as in the figure where θ is the angle of the line $\mathsf{S}-\mathsf{R}-\mathsf{D}$ and d_{AB} denotes the the Euclidean distance between nodes A and B. We suppose that S intends to transmit its own message to D and that R has agreed to forward S's message before the transmission.

All the channel links are disturbed by large-scale path loss, small-scale quasi static frequency nonselective Rayleigh fading, and additive white Gaussian noise (AWGN) with zero mean and noise variance $\sigma^2 = N_0/2$ where N_0 denotes the one-sided power spectrum density. Thus, the complex fading coefficients h_{SR}, h_{SD}, and h_{RD} in Fig. 1 are uncorrelated

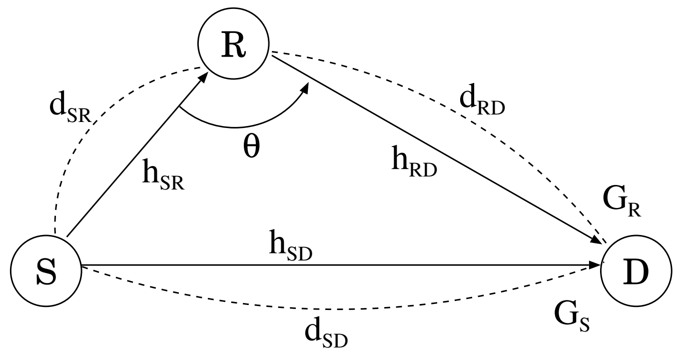

Fig. 1. Geometrical system model with three nodes: source, relay, and destination.

and circularly symmetric complex Gaussian random variables with zero mean and unit variance where these coefficients are assumed to be ideally available at the receiver sides. In this paper, the large-scale path loss between A and B is modeled as

$$f(\mathsf{A},\mathsf{B}) \triangleq \frac{G_t G_r \lambda^2}{(4\pi d_{\mathsf{AB}})^2}, \tag{1}$$

where G_t and G_r are antenna gains at transmitter and receiver, respectively, and λ is the wavelength.

From the motivation of this work, the geometrical gain due to the proximity of the relay over the destination is significantly important in the scenario with RF energy harvesting. To clarify this effect, we here introduce the relative path loss gain. We assume that the source transmits its own signal with average power P_{S}. Let G_{S} denote the geometrical gain at D from S relative to the link $\mathsf{S} \to \mathsf{R}$, which is simply given by

$$G_{\mathsf{S}} = \frac{f(\mathsf{S},\mathsf{D})P_{\mathsf{S}}}{f(\mathsf{S},\mathsf{R})P_{\mathsf{S}}} \triangleq \left(\frac{d_{\mathsf{SR}}}{d_{\mathsf{SD}}}\right)^2. \tag{2}$$

Similarly, if the relay forwards the received information with the average power P_{R}, the geometrical gain at D from R relative to $\mathsf{S} \to \mathsf{R}$ channel link can be given by

$$G_{\mathsf{R}} \triangleq \left(\frac{d_{\mathsf{SR}}}{d_{\mathsf{RD}}}\right)^2 \frac{P_{\mathsf{R}}}{P_{\mathsf{S}}}. \tag{3}$$

By triangle equality, we have

$$d_{\mathsf{SR}}^2 + d_{\mathsf{RD}}^2 - 2d_{\mathsf{SR}}d_{\mathsf{RD}}\cos\theta = d_{\mathsf{SD}}^2. \tag{4}$$

Let ζ denote the ratio of d_{RD} to d_{SR}, i.e., $\zeta = d_{\mathsf{RD}}/d_{\mathsf{SR}}$. Then, the gain G_{R} can be rewritten as

$$G_{\mathsf{R}} = \frac{1}{\zeta^2}\frac{P_{\mathsf{R}}}{P_{\mathsf{S}}} \triangleq \frac{1}{\zeta^2}\mu, \tag{5}$$

where μ is the transmit power ratio. Note that we assume $\mu < 1$ since the transmit power of S should be even higher than that of R which works only with small harvested energy. Also, the gain G_{S} can be expressed as

$$G_{\mathsf{S}} = \frac{1}{1+\zeta^2 - 2\zeta\cos\theta}. \tag{6}$$

Without loss of generality, we assume $0 \le \theta \le \pi$.

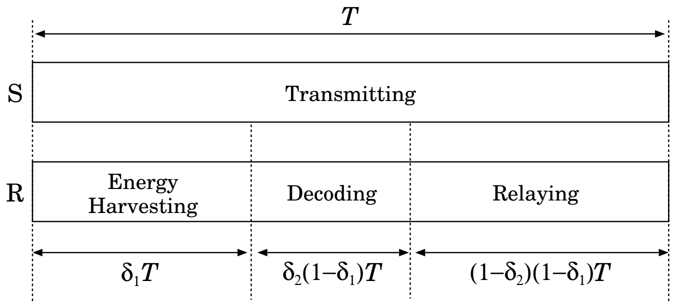

Fig. 2. Dynamic three-phase protocol.

III. Dynamic Harvest-and-Forward Protocol

Based on the model described in the previous section, we here explain our new cooperative protocol with RF energy harvesting. Our dynamic cooperation is composed of three phases depending on relay's behavior: *energy harvesting phase*, *decoding phase*, and *relaying phase*, as illustrated in Fig. 2.

In each transmission block of time duration T, the first $\delta_1 T$ amount of time $(0 < \delta_1 < 1)$ is assigned to harvest the energy from received RF waves. The remaining $(1-\delta_1)$ transmission block is further divided into two parts by δ_2 where $0 < \delta_2 < 1$. During the first $\delta_2(1-\delta_1)T$ duration, the relay intends to decode the source's message. Because of the proximity advantage of the relay over the destination, the relay successfully decode immediately with high probability. Then, the remaining duration $(1-\delta_2)(1-\delta_1)T$ would be utilized for cooperative transmission similar to DDF protocol [19]–[22] where the relay forwards the message only by means of harvested energy E_H. At the destination, the received signals are maximally combined. Hereinafter, $T = 1$ is assumed for simplicity without loss of generality.

When the source transmit with average power P_{S}, the energy harvested at the relay E_H is denoted as

$$E_H = \eta\delta_1 \frac{h_{\mathsf{SR}}^2}{d_{\mathsf{SR}}^2} P_{\mathsf{S}}, \tag{7}$$

where η is a conversion efficiency from alternative current (AC) to direct current (DC) and its practical value is 0.37 according to [13]. It is worth noting that the distances are normalized by d_{SR} and thus $d_{\mathsf{SR}} = 1$ in the rest of the paper.

Upon the harvesting phase, the relay activates its own receiver circuit and starts to decode the information with $\delta_2(1-\delta_1)$ time duration where δ_2 can be dynamically chosen according to every decoding result. Note that we assume that the processing gain to decode the information is negligible. Due to the proximity advantage of the relay, it might successfully decode the information before the destination does.

Finally, the relay forwards the decoded information during the remaining time fraction $(1-\delta_2)(1-\delta_1)$ and its transmission power is given by

$$P_{\mathsf{R}} = \frac{E_H}{(1-\delta_2)(1-\delta_1)} = \frac{\eta\delta_1 h_{\mathsf{SR}}^2 P_{\mathsf{S}}}{d_{\mathsf{SR}}^2(1-\delta_2)(1-\delta_1)}. \tag{8}$$

From the above equation, the transmit power ratio μ is written by

$$\mu = \frac{\eta\delta_1 h_{\mathsf{SR}}^2}{d_{\mathsf{SR}}^2(1-\delta_2)(1-\delta_1)}. \tag{9}$$

Clearly, this proposed approach does not reduce the bandwidth efficiency unlike conventional AF or DF cooperation. Moreover, the relay works only with the harvested energy and thus does not need any extra energy for cooperation.

IV. Outage Probability Analysis

In this section, we analyze the outage probability of proposed DHF protocol. The outage event is defined as follows; unless the system achieves the capacity equals to or greater than the given desired transmission rate R, this event is called *outage*. The outage probability explains the probability that this event occurs and also can be seen as a complementary cumulative distribution function (CCDF) of the non-ergodic capacity.

Upon energy harvesting phase δ_1, the relay starts to decode the information. The time duration of decoding phase is defined by the instantaneous signal-to-noise ratio (SNR) at R. The instantaneous SNR at R is written by

$$h_{\mathsf{SR}}^2 \frac{P_{\mathsf{S}}}{d_{\mathsf{SR}}^2 N_0} \triangleq h_{\mathsf{SR}}^2 \Gamma_{\mathsf{SR}}, \tag{10}$$

where Γ_{AB} is an average SNR of the link $\mathsf{A} \to \mathsf{B}$.

For given R and δ_1, the condition to successfully decode the information during the decoding phase is

$$\delta_2(1-\delta_1)\log_2(1 + h_{\mathsf{SR}}^2\Gamma_{\mathsf{SR}}) \geq R. \tag{11}$$

Thus, the fraction of remaining time δ_2 for decoding is given by

$$\delta_2 = \frac{R}{(1-\delta_1)\log_2(1 + h_{\mathsf{SR}}^2\Gamma_{\mathsf{SR}})}. \tag{12}$$

Clearly, the relay cannot cooperate when $\delta_2 \geq 1$. Namely, there is no remaining time for cooperation. This probability is referred to as *cooperation probability* and denoted by $\Pr[\delta_2 \geq 1]$. Considering the distribution of h_{SR}^2, the probability can be easily calculated as

$$\Pr[\delta_2 \geq 1] = \exp\left[-\left(\frac{2^{\frac{R}{1-\delta_1}} - 1}{\Gamma_{\mathsf{SR}}}\right)\right]. \tag{13}$$

The average SNR of the link $\mathsf{S} \to \mathsf{D}$ is simply expressed as $\Gamma_{\mathsf{SD}} = G_{\mathsf{S}}\Gamma_{\mathsf{SR}}$ from the relationship given by (6). Unless the relay is available at the relaying phase, the resulting achievable rate is calculated by

$$C_D(h_{\mathsf{SD}}, \Gamma_{\mathsf{SD}}) = \log_2(1 + h_{\mathsf{SD}}^2 G_{\mathsf{S}}\Gamma_{\mathsf{SR}}). \tag{14}$$

Then, the outage probability of this transmission becomes

$$\Pr[C_D < R] = 1 - \exp\left[-\frac{2^R - 1}{G_{\mathsf{S}}\Gamma_{\mathsf{SR}}}\right]. \tag{15}$$

If the relay is available, the source solely transmits during the first $(\delta_1 + \delta_2(1-\delta_1))$ amount of time and the source and

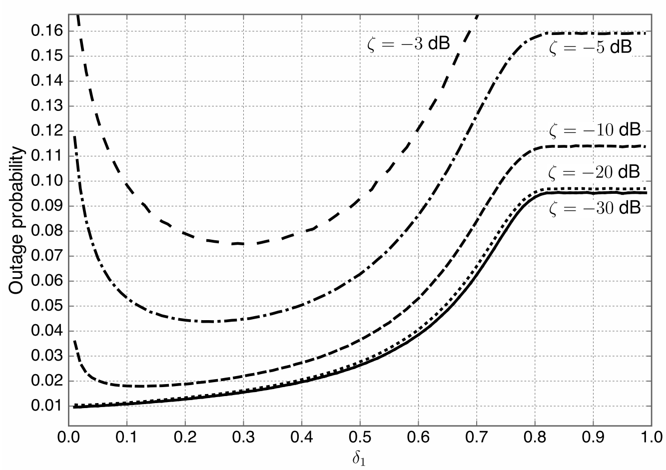

Fig. 3. The effect of δ_1 with different geometrical arrangement ζ where $R = 1.0$, $\theta = \pi$, and $\eta = 0.37$. Also Γ_{SD} is set to be $30\,\mathrm{dB}$ when $\zeta = -30\,\mathrm{dB}$.

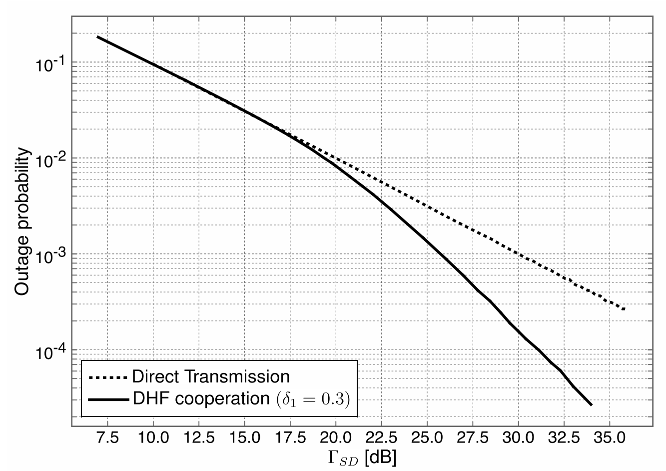

Fig. 4. The outage probability performance of direct transmission and DHF cooperation with $\delta_1 = 0.3$ where $R = 1.0$, $\theta = \pi$, $\eta = 0.37$, and $\zeta = -30\,\mathrm{dB}$.

relay cooperatively transmit during remaining fraction of time. The achievable rate during relaying phase is calculated by

$$\begin{aligned} C_C(h_{\mathsf{SD}}, h_{\mathsf{RD}}, \Gamma_{\mathsf{SD}}, \Gamma_{\mathsf{RD}}) &= \log_2(1 + h_{\mathsf{SD}}^2 G_{\mathsf{S}} \Gamma_{\mathsf{SR}} + h_{\mathsf{RD}}^2 G_{\mathsf{R}} \Gamma_{\mathsf{SR}}) \\ &= \log_2(1 + h_{\mathsf{SD}}^2 G_{\mathsf{S}} \Gamma_{\mathsf{SR}} \\ &\quad + \frac{\eta \delta_1}{\zeta^2 d_{\mathsf{SR}}^2 (1-\delta_1)(1-\delta_2)} h_{\mathsf{SR}}^2 h_{\mathsf{RD}}^2 \Gamma_{\mathsf{SR}}) \end{aligned} \quad (16)$$

Hence, the overall achievable rate of proposed protocol with relaying phase is simply given by

$$C_H = (\delta_1 + \delta_2(1-\delta_1))C_D + (1-\delta_1)(1-\delta_2)C_C, \quad (17)$$

where apparent variables are dropped off in the above equation for simplicity. Unfortunately, the outage probability $\Pr[C_H < R]$ does not admit the closed form and we should resort to Monte Carlo calculation.

Finally, the overall outage probability of the system can be calculated by

$$\begin{aligned} P_{\mathrm{out}} = \Pr[\delta_2 \geq 1] \Pr[C_D < R] \\ + (1 - \Pr[\delta_2 \geq 1]) \Pr[C_H < R]. \end{aligned} \quad (18)$$

V. Numerical Results

In this section, we present some numerical results to demonstrate the advantage of our proposed DHF cooperation. In the following, we assume that $R = 1.0$ and $\eta = 0.37$.

A. Effect of δ_1

Figure 3 exhibits the effect of δ_1 with different geometrical arrangement ζ in terms of outage probability where $\theta = \pi$. Also Γ_{SD} is set to be $30\,\mathrm{dB}$ when $\zeta = -30\,\mathrm{dB}$. Note that, when ζ decreases, it can be intuitively interpreted as that D is placed farther away than R since the distances are normalized by the distance between S and R, i.e., $d_{\mathsf{SR}} = 1$.

When $\zeta = -20\,\mathrm{dB}$ and $-30\,\mathrm{dB}$ (namely, the destination is placed nearby the relay), the smaller δ_1 achieves the better performance since the relay can obtain sufficient energy from the source's transmission in a short duration to reliably forward the received information. However, when ζ becomes large, the longer duration of energy harvesting phase is needed as obvious from the figure (e.g., the case of $\zeta = -3\,\mathrm{dB}$). As larger δ_1 is chosen, the cooperation probability (13) decreases. Therefore, the relay is not available with high probability even though the required energy is harvested, as observed at the region of $\delta_1 > 0.5$ in the figure.

In order to obtain the optimum performance of DHF cooperation, the relay has to dynamically determine the adequate duration of energy harvesting phase δ_1 based on parameters of all the channel links. However, it imposes the additional consumption of resources in the network and contradicts the motivation of this work. Therefore, judicious choice of δ_1 is from 0.2 to 0.4 since these values provide the reasonable performance at the region that the availability of relay is effective. Therefore, $\delta_1 = 0.3$ is chosen as an example in the following.

B. Comparison of Outage Probability Performance

Figure 4 shows the outage probability performance of direct transmission without RF energy harvesting relay and DHF cooperation with $\delta_1 = 0.3$ where we assume that $\theta = \pi$ and $\zeta = -30\,\mathrm{dB}$.

As observed from the figure, the proposed approach achieves diversity order of two at high SNR region while the performance of DHF cooperation is almost identical to that of direct transmission at low SNR region. Unlike conventional cooperative communications, our approach does not consume any energy in the network and thus the performance of DHF cooperation is not inferior to that of direct transmission even at low SNR region.

C. Effect of ζ

Finally, the effect of ζ with fixed δ_1 is shown in Fig. 5 where $\delta_1 = 0.3$ and $\theta = \pi$. Also, P_{S} and N_0 are assumed

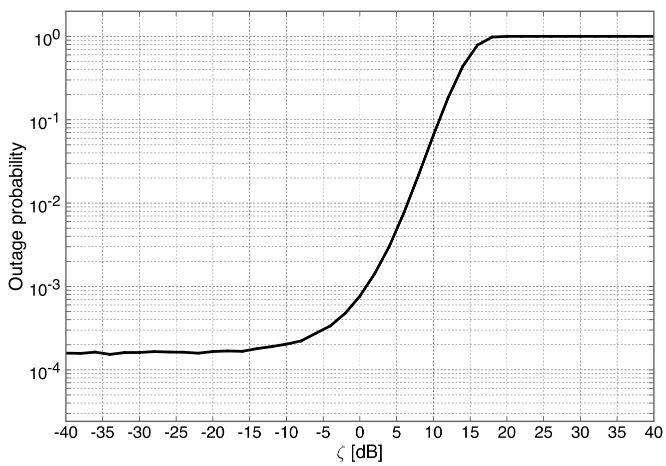

Fig. 5. The effect of geometrical arrangement ζ where $R = 1.0$, $\delta_1 = 0.3$, $\theta = \pi$, and $\eta = 0.37$. Also, P_S and N_0 are $10\,[\text{mW}]$ and 0.01, respectively.

to be $10\,[\text{mW}]$ and 0.01, respectively. Until $\zeta = -10\,\text{dB}$, the performance seems almost constant. However, once ζ exceed $-10\,\text{dB}$, the outage probability steeply rises. This observation indicates the relationship between the available harvested energy and the geometrical region where the relay effectively works. It is worth noting that, in this paper, d_SR is normalized (fixed) but, when the distance d_SR becomes longer, it is necessary to increase the source's transmit power P_S in order to achieve the similar performance.

VI. Conclusion

In this paper, we have proposed effective diversity technique with RF energy harvesting named DHF cooperation. The outage probability of DHF cooperation has been analyzed. Numerical results showed that this cooperation enables to obtain full diversity gain (i.e., diversity order of two) with consuming neither extra energy nor extra bandwidth by exploiting the relay's proximity advantage over the destination. Moreover, the advantageous region of DHF cooperation was demonstrated based on the geometrical model.

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