RF Energy Powered Feedback-Aided Cooperation

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***Abstract*—In this paper, we propose a radio-frequency (RF) energy powered cooperative transmission using RF energy harvesting which scavenges the energy from ambient radio waves. The outage probability of this system is theoretically analyzed to show the advantageous region compared with the direct transmission without RF energy harvesting relay when amplify-and-forward (AF) and decode-and-forward (DF) relaying are employed. Moreover, if the source can get the information about the residual battery and decoding results of the relay, the source can recognize the availability of relay and resources. Thus, we propose feedback-aided cooperation with RF energy harvesting, which can exploit all the available resources in the network, and show that utilizing the explicit or implicit feedback information significantly improves the overall performance.**

I. Introduction

For battery-limited applications such as sensor networks which autonomously collect environmental information such as temperature and humidity, robustness and low energy consumption are more important design factors than higher data rate to realize *long time* and *real-time* observations. Typical wireless channels, however, 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], it is practically difficult to equip multiple antennas to sensors because of the size, complexity, and cost. Hence, 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 a pre-charged battery, which is called *cooperative diversity* and allows nodes to enjoy spatial diversity gain without equipping additional antennas [2]. 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, energy-efficient relaying has been proposed in [3] based on decode-and-forward (DF) relaying to enhance the power amplifier (PA) efficiency at the relay.

Even with the energy-efficient relaying, the cooperation still consumes additional energy from pre-charged battery, which may result 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 [4] in combination with cooperative diversity [5], [6]. Energy harvesting makes it possible to scavenge energy from solar, vibration, wind, ambient electromagnetic waves and so on in order to recharge the battery. The performance of cooperative communication with multiple energy harvesting relays has been studied in [5] and the advantage of using relays was shown where the energy harvested by the relay was 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 [6], wireless energy transfer such as radio-frequency (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 signals. Furthermore, one-hop amplify-and-forward (AF) relaying with practical finite pre-charged battery model has been studied in [7] 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 pre-charged battery and consumes its own energy.

The question that may arise here is how much gain we can obtain when the relay only utilizes the energy harvested from the received signals. In [8], [9], three phase cooperative transmission has been investigated where the relay forwards the received information only with the harvested energy. However, the effect of finite-size battery of the relay has not been considered in the literature. Therefore, in this paper, we investigate an RF energy powered cooperative relaying with the finite-size battery. Specifically, the outage probability of this system is theoretically analyzed to show the advantageous region compared with the direct transmission without RF energy harvesting relay when AF and DF relaying are employed as relaying function. Moreover, if the source can get the information about the residual battery and decoding results of the relay, the source can recognize the availability of all the resources in the network. Thus, we propose *feedback-aided cooperation* with RF energy harvesting, which can efficiently exploit all the available resources in the network.

The paper is organized as follows. Section II describes the system model treated in the paper and proposed cooperation is described. In Section III, we derive outage probability of cooperative transmissions with RF energy harvesting using state transition matrix and show the diversity order of the proposed approach. Numerical results confirm theoretical analyses and clarify the advantageous region of RF energy harvesting relay without external energy in Section IV. Finally, Section V concludes this work.

II. System Model

In this paper, we assume that the network is composed of three nodes, source (S), relay (R), and destination (D), and each node equips a single antenna. Due to the half-duplex constraint, every node cannot simultaneously transmit and receive. Thus, when the relay is available, every transmission is performed in two phases. Also, we assume that relay has the RF energy harvesting capability and the battery with finite size $P_b \geq 0$ where the residual battery $e = 0$ at the beginning of transmissions since the relay only utilizes the energy harvested from received signals.

In the first phase, the source broadcasts its own information during $T/2$ duration over wireless channels. Then, the received signal at the time instant $t = 1, 2, \cdots$ at R and D can be respectively expressed by

$$y_{\mathrm{SR}}^{(1)}(t) = \sqrt{P_{\mathrm{S}}} h_{\mathrm{SR}} \sqrt{G_{\mathrm{SR}}} x(t) + n_{\mathrm{R}}^{(1)}(t) \quad (1)$$

$$y_{\mathrm{SD}}^{(1)}(t) = \sqrt{P_{\mathrm{S}}} h_{\mathrm{SD}} \sqrt{G_{\mathrm{SD}}} x(t) + n_{\mathrm{D}}^{(1)}(t), \quad (2)$$

where $x(t)$ is a complex transmit signal with unit power, $n_{\mathrm{j} \in \{\mathrm{R,D}\}}$ is additive white Gaussian noise (AWGN) with zero mean and variance $N_j = \sigma^2$, P_{S} is the transmit power of source, and h_{ij} is the channel coefficient between node $i \in \{\mathrm{S}, \mathrm{R}\}$ and j following a complex Gaussian distribution with zero mean and unit variance. In the paper, frequency non-selective block Rayleigh fading is assumed and thus the coefficients are constant during each transmission block. Also, G_{ij} denotes the path-loss coefficient which is given by $G_{ij} = (1 + d_{ij}^{\beta})^{-1}$ where d_{ij} is the distance between node i and j, and β denotes the path-loss exponent practically ranging from 2 to 4. Without loss of generality, β is assumed to be 2 in the rest of the paper. Note that the path-loss coefficient is regularly modeled as $1/d_{ij}^{\beta}$ rather than $(1 + d_{ij}^{\beta})^{-1}$ [10]. This typical function, however, might be greater than one when the distance d_{ij} is smaller than one while no receiver can obtain more power than was transmitted. In this case, an alternative option is the use of minimum possible path-loss degradation which ensures the accuracy of path-loss model for short distances [11], [12].

During the source transmission, the relay switches two modes (either harvesting or relaying) according to its own residual battery $0 \leq e \leq P_b$. Let E_{R} denote the transmit energy of the relay and the relay's battery size is given by $P_b = \alpha E_{\mathrm{R}}$ where $\alpha \geq 1$.

When $e < E_{\mathrm{R}}$, the relay works in harvesting mode and scavenges the power from received RF signals and the harvested energy e_h is defined as

$$e_h \triangleq \eta P_{\mathrm{S}} |h_{\mathrm{SR}}|^2 G_{\mathrm{SR}} \times T_H, \quad (3)$$

where T_H denotes the time duration for energy harvesting and $\eta (0 < \eta \leq 1)$ denotes the conversion efficiency, $100 \times \eta\%$ of the received energy can be stored. Thus, the resulting battery after RF energy harvesting is given by $\min(P_b, e + e_h)$. On the other hand, if $e \geq E_{\mathrm{R}}$, the relay works in relaying mode and receives the information and forwards it consuming own battery. Upon forwarding in the second phase, the remaining battery is given by $\max(0, e - E_{\mathrm{R}})$ which decides the behavior of relay at the first phase in the next transmission.

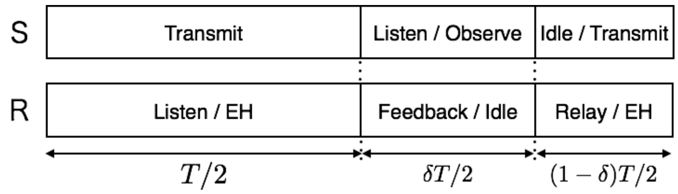

Fig. 1. The protocol of the source and the relay in the proposed feedback-aided cooperation.

A. AF Relaying

In AF relaying, the relay scales and amplifies the received signals and thus neither decoding nor demodulation is needed. Then, the received signal at the destination node in the second phase is written by

$$y_{\mathrm{SRD}}^{(2)}(t) = \sqrt{P_{\mathrm{R}}} h_{\mathrm{RD}} \sqrt{G_{\mathrm{RD}}} K_{\mathrm{SR}} y_{\mathrm{SR}}^{(1)}(t) + n_{\mathrm{D}}^{(2)}(t), \quad (4)$$

where P_{R} denotes the transmit power of the relay, given as $P_{\mathrm{R}} = E_{\mathrm{R}}/T_{\mathrm{C}}$ using the time duration for relaying T_{C}, and K_{SR} is an amplification factor which is given by

$$K_{\mathrm{SR}} = \left(\sqrt{P_{\mathrm{S}} |h_{\mathrm{SR}}|^2 G_{\mathrm{SR}} + N_{\mathrm{R}}} \right)^{-1}. \quad (5)$$

The node D combines two received signals given by (2) and (4) using maximum ratio combining (MRC).

B. DF Relaying

In the DF relaying, if and only if the relay has correctly decoded the information, it re-encodes and forwards the information with regenerated symbols $z(t)$ with unit average power. Then, the received signal at the destination node is expressed as

$$y_{\mathrm{RD}}^{(2)}(t) = \sqrt{P_{\mathrm{R}}} h_{\mathrm{RD}} \sqrt{G_{\mathrm{RD}}} z(t) + n_{\mathrm{D}}^{(2)}(t). \quad (6)$$

In this paper, we assume that the relay transmits additional codewords similar to *incremental redundancy* (IR) or distributed coding to efficiently obtain both diversity and coding gain upon decoding with (2) and (6).

C. Feedback-Aided Cooperation with RF Energy Harvesting

If the source can get the information about the residual battery of the relay, the source can exploit the available wireless resource in the second phase. For example, if the residual battery of the relay does not exceed E_{R}, the source utilizes the second phase to transmit its own information while the relay continues to harvest the energy. Moreover, if the source recognize the failure decoding of the DF relay at the end of the first phase, the source can transmit even in the second phase while the relay charges its own battery from the received RF waves. This approach is called *feedback-aided cooperation* in the rest of the paper and its protocol is illustrated in Fig. 1.

In this paper, we consider two different feedback schemes: *explicit* and *implicit* feedback. In case of explicit feedback, the relay transmits a small packet reporting both its residual battery and the decoding result during $\delta T/2$ time duration. In case of implicit feedback, the source detects the relay's behavior (i.e., in transmission or idle) for the short time duration $\delta T/2$ and recognizes the availability of resources in the network. Upon $\delta T/2$ time duration, the source decides either to be idle or to transmit with the aid of the feedback information. Note that the explicit feedback consumes additional energy during $\delta T/2$ time duration but the implicit one.

III. Outage analysis with state transition matrix

In this section, the outage probability of cooperative transmissions described in Section II is theoretically analyzed. The outage event occurs when the instantaneous channel capacity derived from the instantaneous signal-to-noise ratio (SNR) is less than the given target rate R. Thus, the outage probability of the system is simply written as

$$P_{\mathrm{out}} = P_{\mathrm{A}} P_{\mathrm{out}}^{\mathrm{C}} + (1 - P_{\mathrm{A}}) P_{\mathrm{out}}^{\mathrm{H}}, \tag{7}$$

where $P_{\mathrm{out}}^{\mathrm{C}}$ and $P_{\mathrm{out}}^{\mathrm{H}}$ respectively indicate the outage probability of relaying mode and harvesting mode. Moreover, P_{A} is the probability that the relay is available. This obviously depends on the statistical behavior of the battery with RF energy harvesting, which will be thoroughly discussed in the subsequent subsections. Hereinafter $T = 1$ is assumed for simplicity without loss of generality.

A. Outage Probability of AF Relaying

1) With Explicit Feedback: When the explicit feedback is available and the relay is in the energy harvesting mode, the relay can harvest energy in both phases. Thus, the harvesting duration is extended to $T_H = (2 - \delta)/2$ while the relay consumes extra power δE_{R} from its own battery for feedback. Moreover, unless the relay is available, the source transmits even in the second phase.

Hence, when the relay is available (i.e., relaying mode), the outage probability of AF relaying $P_{\mathrm{out}}^{\mathrm{C}}$ at high SNR region can be approximately given by [2]

$$\begin{aligned} P_{\mathrm{out}}^{\mathrm{C}} &= \Pr\left[\frac{1-\delta}{2}\log_2(1+\gamma_{\mathrm{SD}}+\gamma_{\mathrm{SRD}}) < R\right] \\ &\sim \frac{(2^{\frac{2}{1-\delta}R}-1)^2}{2}\bar{\gamma}_{\mathrm{SD}}^{-1}\bar{\gamma}_{\mathrm{SRD}}^{-1}. \end{aligned} \tag{8}$$

On the other hand, when the relay is in the harvesting mode, the outage probability is given by

$$\begin{aligned} P_{\mathrm{out}}^{\mathrm{H}} &= \Pr\left[\frac{2-\delta}{2}\log_2(1+\gamma_{\mathrm{SD}}) < R\right] \\ &= 1 - \exp\left(-\frac{2^{\frac{2}{2-\delta}R}-1}{\bar{\gamma}_{\mathrm{SD}}}\right), \end{aligned} \tag{9}$$

where γ_{SD} is the instantaneous SNR from the node S to the node D, γ_{SRD} is that from the node S to the node D through the node R, and $\bar{x}$ denotes the mean of random variable x.

2) With Implicit Feedback: On the other hand, when the implicit feedback is utilized, the source autonomously detects the relay's behavior (in transmission or idle) without consuming extra energy from the battery. Based on the observation result, the source decides the behavior in the second phase. Therefore, the outage probability in relaying mode equals to the equation (8) with $\delta = 0$ and that in harvesting mode equals to equation (9).

B. Outage Probability of DF Relaying

1) With Explicit Feedback: In case of DF relaying, $P_{\mathrm{out}}^{\mathrm{C}}$ depends on whether the relay successfully decodes the information or not. Thus, the outage probability between the source and the relay is calculated by

$$\begin{aligned} P_{\mathrm{decode}} &= \Pr\left[\log_2(1+\gamma_{\mathrm{SR}}) > R\right] \\ &= 1 - \exp\left(-\frac{2^R - 1}{\bar{\gamma}_{\mathrm{SR}}}\right), \end{aligned} \tag{10}$$

where γ_{SR} is the instantaneous SNR from the source to the relay. In the DF relaying, the relay may fail to decode even if it has the enough residual battery. In this case, the source can utilize the available time slot and the relay can harvest RF signals. Then, when the relay fails to decode, the channel capacity is given by $C_{\mathrm{H}} = \frac{2-\delta}{2}\log_2(1+\gamma_{\mathrm{SD}})$. Then, the outage probability $\Pr[C_{\mathrm{H}} < R]$ is similarly calculated by (9).

In case of the relaying mode, the resulting capacity is denoted by

$$C_{\mathrm{C}} = \frac{1-\delta}{2}\{\log_2(1+\gamma_{\mathrm{SD}}) + \log_2(1+\gamma_{\mathrm{RD}})\}. \tag{11}$$

Then, using Jensen's inequality, the outage probability $\Pr[C_{\mathrm{C}} < R]$ is calculated as

$$\begin{aligned} &\Pr\left[\frac{1-\delta}{2}\{\log_2(1+\gamma_{\mathrm{SD}}) + \log_2(1+\gamma_{\mathrm{RD}})\} < R\right] \\ &\leq \Pr\left[|h_{\mathrm{SD}}|^2\bar{\gamma}_{\mathrm{SD}} + |h_{\mathrm{RD}}|^2\bar{\gamma}_{\mathrm{RD}} < 2(2^{\frac{R}{1-\delta}} - 1)\right] \\ &\sim 2(2^{\frac{R}{1-\delta}} - 1)^2\bar{\gamma}_{\mathrm{SD}}^{-1}\bar{\gamma}_{\mathrm{RD}}^{-1}, \end{aligned} \tag{12}$$

where γ_{RD} is instantaneous SNR from relay to destination.

From (9) and (12), the outage probability of proposed cooperation with DF relaying is given by

$$P_{\mathrm{out}}^{\mathrm{C}} = (1 - P_{\mathrm{decode}})\Pr[C_{\mathrm{C}} < R] + P_{\mathrm{decode}}\Pr[C_{\mathrm{H}} < R]. \tag{13}$$

2) With Implicit Feedback: When the implicit feedback is used together with DF relaying, the outage probability is obtained as similar to the AF relaying and thus the details of derivation are here omitted due to limitations of space.

C. Available Probability

As described in the previous section, the residual battery continuously changes according to the received energy and this defines the available probability of the relay. In order to analyze this probability, the discretized battery model with $(L+2)$ levels is introduced [7], which is expressed as

$$e_x \triangleq \frac{xP_b}{L+1}, \ x = 0, 1, \ldots, L+1 \tag{14}$$

In discretized battery model, harvesting energy e_h and energy consumption $E_{\rm R}$ are respectively defined as follow:

$$e_h \triangleq e_{i_h} \quad \text{s.t.} \quad i_h = \mathop{\arg\max}_{i_h \in \{0,1,\dots,L+1\}} \{e_{i_h} < e_h\} \tag{15}$$

$$E_{\rm R} \triangleq e_{i_r} \quad \text{s.t.} \quad i_r = \mathop{\arg\min}_{i_r \in \{0,1,\dots,L+1\}} \{e_{i_r} \geq E_{\rm R}\}. \tag{16}$$

The state of the battery is defined by

$$\mathsf{S}_k = \text{State[residual battery is } e_k], \tag{17}$$

and corresponding transition probability from state S_a to state S_b is defined as

$$\mathsf{E}_{a,b} = \text{Event[transit from state } \mathsf{S}_a \text{ to state } \mathsf{S}_b]. \tag{18}$$

Then, all the transition events are classified as follow.

1) $\mathsf{E}_{0,0}$: The battery remains empty.
2) $\mathsf{E}_{0,i}$ $(0 < i < L+1)$: The empty battery is partially charged.
3) $\mathsf{E}_{0,L+1}$: The empty battery is fully charged.
4) $\mathsf{E}_{i,i}$ $(0 < i < L+1)$: The non-empty battery remains constant.
5) $\mathsf{E}_{i,j}$ $(0 < i < j < L+1)$: The non-empty battery is partially charged.
6) $\mathsf{E}_{i,L+1}$ $(0 < i < L+1)$: The non-empty battery is fully charged.
7) $\mathsf{E}_{L+1,L+1}$: The battery remains full.
8) $\mathsf{E}_{j,i}$ $(j > i)$: The battery is discharged.

These transition probabilities are simply calculated by exponential distribution as discussed in [7].

Then, using these state transition probabilities, state transition matrix $\mathbf{P}$ is expressed as follows.

$$\mathbf{P} = \begin{pmatrix} P(\mathsf{E}_{0,0}) & P(\mathsf{E}_{0,1}) & \cdots & P(\mathsf{E}_{0,L+1}) \\ P(\mathsf{E}_{1,0}) & P(\mathsf{E}_{1,1}) & \cdots & P(\mathsf{E}_{1,L+1}) \\ \vdots & \vdots & \ddots & \vdots \\ P(\mathsf{E}_{L+1,0}) & P(\mathsf{E}_{L+1,1}) & \cdots & P(\mathsf{E}_{L+1,L+1}) \end{pmatrix}$$

State transition matrix at $t = T_o$ is expressed as $\mathbf{P}^{T_o}$. Assuming that $(\cdot)_{a,b}$ is the element of a row b column, the relay's available probability at $t = T_o$ is expressed as follows.

$$P_{\rm A} = \sum_{b=k}^{L+1} \left(\mathbf{P}^{T_o}\right)_{a,b} \quad \text{s.t.} \quad k = \mathop{\arg\min}_{k \in 0,1,\dots,L+1} \{e_k > E_{\rm R}\} \tag{19}$$

D. Diversity Order Analysis of Proposed Cooperation

Based on the above analyses, we further elaborate the achievable diversity order of the proposed approach. From (8) and (12), the relaying transmissions seem to achieve the diversity order of two. However, since the relay transmits with constant power $P_{\rm R}$ regardless of the received SNR, neither AF nor DF relaying achieves the diversity order of two. In contrast, the three-phase RF energy harvesting cooperation proposed in [8], [9] achieves the diversity order of two since the relay boosts up its own transmit power according to the instantaneous received power (i.e., harvested energy).

TABLE I
SIMULATION PARAMETERS

$d_{\rm SR}[m]$	2.0, 5.0	α	100
$d_{\rm RD}[m]$	28.0	β	2.0
$d_{\rm SD}[m]$	30.0	η	0.37
N_0	0.0001	L	100
$E_{\rm R}$	1.0	δ	0.1

IV. NUMERICAL RESULTS

Numerical results are presented in this section to confirm the statements in the previous section and to evaluate the advantage of the feedback-aided cooperation. The common parameters are listed in Table I where the conversion efficiency η is assumed to be 0.37 as a practical value [13].

A. Outage Performance Comparisons

Figure2 shows the outage probabilities of direct transmission, AF and DF cooperation without feedback, explicit-feedback-aided AF and DF cooperation, and implicit-feedback-aided AF and DF cooperation where $d_{\rm SR}$ is assumed to be 2.0[m]. Note that the battery of the relay is not charged at all at the beginning of transmissions and thus the relay does not consume any external energy. Theoretical curves derived in the previous section are also drawn in the figure. As observed from the figure, all the results calculated by the derived equations show good agreement with those obtained by Monte-Carlo simulations. Moreover, the outage probabilities of proposed feedback-aided cooperation with AF or DF relaying are superior to that of direct transmission where DF cooperation with implicit feedback exhibits the best performance. Comparing the implicit-feedback-aided DF cooperation with that without feedback, the additional gain is about $3.0\,$dB at 10^{-4}. This fact clearly indicates that the source and relay can efficiently exploit available resources based on the feedback information. Also, compared with direct transmission, the implicit-feedback-aided DF cooperation obtains about $7.0\,$dB additional gain at 10^{-4}. Note that the diversity order of the proposed cooperation approaches to one as the SNR increases, which is anticipated in the previous section. Thus, the proposed approach cannot increase the diversity order although it still provides significant gain at moderately high SNR region.

In order to show the effect of proximity of the relay, Fig.3 shows the outage performances with $d_{\rm SR} = 5.0[\text{m}]$. The other parameters are same as Fig.2. Comparing these figures, the performance gap between direct transmission and proposed feedback-aided cooperation becomes smaller as the distance between the source and the relay increases. It is, hence, clear that the relay should be placed nearby the source to efficiently harvest the energy from the received RF waves.

B. Effect of δ

Finally, we evaluate the effect of duration δ on explicit-feedback-aided and implicit-feedback-aided DF cooperation in terms of outage probability. Also, we assume that $\bar{\gamma}_{\rm SD} = 30\,$dB ($P_{\rm S} = 100[\text{mW}]$) and $d_{\rm SR} = 2.0[\text{m}]$ and the other parameters

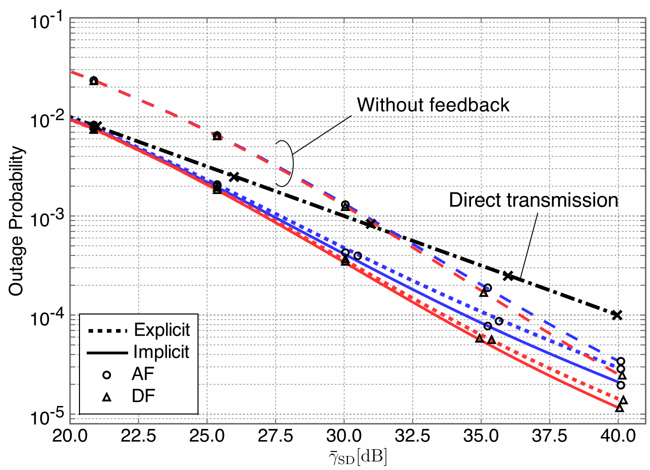

Fig. 2. Outage probability performances of direct transmission, AF and DF cooperation without feedback, explicit-feedback-aided AF and DF cooperation, and implicit-feedback-aided AF and DF cooperation when $d_{\mathrm{SR}} = 2[m]$

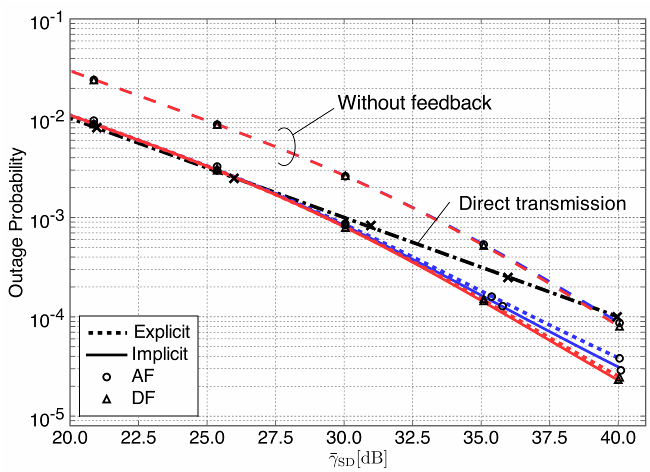

Fig. 3. Outage probability performances of direct transmission, AF and DF cooperation without feedback, explicit-feedback-aided AF and DF cooperation, and implicit-feedback-aided AF and DF cooperation when $d_{\mathrm{SR}} = 5[m]$

are the same as those in the previous subsection. The outage performances with different δ are shown in Fig.4. The significant performance degradation is observed when the explicit feedback is utilized since increasing δ incurs decreasing the resulting capacity in relaying mode with explicit feedback. Therefore, the explicit feedback not only consumes the relay's battery but also causes the degradation of the overall performance.

V. Conclusions

In this paper, the RF energy powered cooperation system was proposed and its outage probability has been analyzed by using state transition matrix. We have showed that the implicit-feedback-aided DF relaying was the best option to achieve the higher reliability without consuming any extra energy.

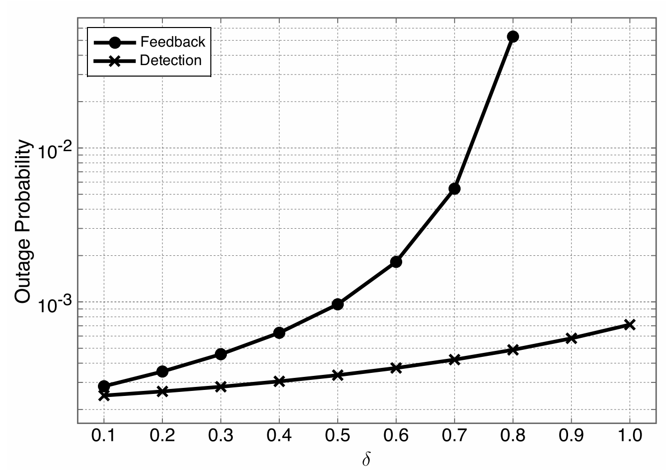

Fig. 4. Outage performance of implicit-feedback-aided DF cooperation with different δ where $d_{\mathrm{SR}} = 2[m]$ and $\bar{\gamma}_{\mathrm{SD}} = 30\,\mathrm{dB}$.

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