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Simultaneous Wireless Information and Power Transfer for Cooperative Relay Networks With Battery

SUMAILA MAHAMA, DEREK KWAKU POBI ASIEDU, AND KYOUNG-JAE LEE, (Member, IEEE)
Department of Electronics and Control Engineering, Hanbat National University, Deajeon 34158, South Korea

Corresponding author: Kyoung-Jae Lee (kyoungjae@hanbat.ac.kr)

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ABSTRACT In this paper, we investigate simultaneous wireless information and power transfer in a cooperative communication network consisting of one source, one battery-enabled relay, and one destination node. An amplify-and-forward relaying method is considered, where the relay node harvests energy from the received signal power to charge its battery, which is used to forward the received signal to the destination. We also consider a direct link between the source and the destination. The direct link signal can be combined with the relaying signal at the destination node using maximum ratio combining. Under the delay-limited transmission mode, closed form expressions for outage probability are derived for a battery-enabled relay. Our analytical results reveal the advantage of cooperative relay networks with a direct link. Also, we extend our design to a multiple-relay scenario, where the best relay is selected from the available number of relays, based on the information of relay locations. Finally, we demonstrate from simulation results based on outage probability that our proposed methods are efficient in comparison with Monte Carlo simulations.

INDEX TERMS SWIPT, amplify-and-forward relay, outage probability, throughput.

I. INTRODUCTION

Cooperative communication networks provide significant improvement of link reliability, throughput and network coverage when the source-destination link suffers from severe fading [1]–[3]. Multiple-antenna systems have been extensively studied in literature as a key approach to combat fading by exploiting the spatial diversity provided by the multiple antennas [4]. However, there are limitations in the implementation of multiple antennas in transceiver design, particularly in user devices. Cooperative relay communication is an efficient way of exploiting spatial diversity through cooperation among distributed wireless nodes [5].

In cooperative relaying network, relay nodes may have limited battery reserves and therefore rely on some external charging mechanism in order to remain active [6]. Replacing or recharging batteries incurs high cost and also limits the flexibility of relay node deployment. For example, when a lot of wireless sensor nodes are deployed in a dangerous environment, replacing or recharging their batteries becomes very inconvenient. In this environment, energy harvesting (EH) provides a safe and cost effective option for powering wireless sensor nodes. Traditional EH methods are based on natural sources such as solar, wind, vibrations, etc. Another source of EH that has received significant attention in the literature is the radio frequency (RF) signal. Unlike the natural sources, RF EH provides a more stable form of energy since it is independent of unrestrainable factors such as weather [7].

Because the RF signal can carry both energy and information simultaneously, there has been significant study in the area of simultaneous wireless information and power transfer (SWIPT) [8]–[12]. SWIPT allows network nodes to harvest energy and decode information from the same RF signal [8], [9]. Varshney [8] investigated the concept of SWIPT from an information theory framework point of view for a noisy narrowband channel. Reference [8] was extended for frequency-selective channels with additive white Gaussian noise (AWGN) in [9]. A two-way noiseless binary communication system was investigated for wireless power and information transmission in [10]. Also, wireless energy harvesting for orthogonal frequency division multiplexing (OFDM) and cognitive radio systems has been studied in [11] and [12], respectively. These articles proved the possibility and potential of wireless power transfer (WPT) in wireless communication.

RF EH in wireless relaying networks has been recently considered in literature [13]–[16]. The outage performance of an amplify-and-forward (AF) relaying network under EH constraints, assuming perfect channel knowledge is studied in [13] and [14]. In [13], an RF energy transfer concept based on switching between data relaying and EH is studied. Reference [13] didn't consider a direct link between source and destination. Also, Inforamtion and power were not simultanously transmitted in [13]'s system model. Reference [14] evaluates the outage behavior of an EH relay-aided cooperative network with multiple relay nodes. Simple relay strategies were studied in [14] intead of optimal transmission strategies. Reference [14] also compared cooperative protocols for stable power supply and energy harvesting. Also, the throughput performance of an AF relaying network under energy harvesting constraints was investigated in [15]. Time-switching and power splitting optimal protocols were developed for delay-limited and delat-tolerant transmisson modes respectively in [15]. Reference [15] did not consider a direct link between source and destination.

A recent work in [16] has considered a multiple-relay system with relay selection, in which they derived a closed form expression for the outage probability of a batteryless relay and relays with baterries. Reference [16] compared relay selection performance between a batteryless relay and a relay with bateery. Also, [16] assumed no direct communication between source and destination. Lee *et al.* [17] investigated the outage probability analysis of a SWIPT relaying system in the presence of a direct link. All, the reviewed papers presented above studied cooperative networks for either a relay node with a battery or a batteryless relay. Another practical scenario will be to study the behavior of a system with a rechargeable battery. This scenario can be used for maintaining self sustaining/recharging isolated and embedded nodes/sensors via WPT.

In this paper, we first consider an AF cooperative communication network with one source node, one destination node, and one battery-enabled (B-E) EH relay node. We adopt the power splitting-based relaying (PSR) protocol at the relay [15]. It is assumed that there is a direct link between the source and the destination nodes. The relay in the AF mode assists the transmission from the source to the destination by employing maximum ratio combining (MRC) at the destination node. We derive closed-form expressions for outage probability of the cooperative AF relaying system in a delay-limited transmission environment for the relay with battery.

We then extend our results to a multiple-relay scenario adopting relay selection based on the outage probability analysis derived for the single relay case. In this case, the best relay is chosen to forward the source signal to the destination node. In a situation with multiple relay nodes, the proposed relay selection scheme is practical since it needs only the information of the distances between source, relay, and destination nodes [3], [18]. Simulation results show that, although more time slots are needed in cooperative communication, compared to direct transmission, the outage performance is improved significantly by employing EH relay nodes.

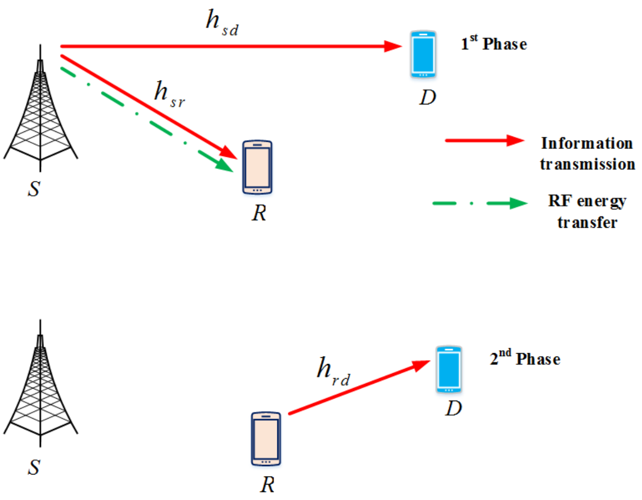

FIGURE 1. System model.

The paper is organized as follows: Section II describes the system model. Section III outlines the outage behavior of the proposed system model. In Section IV, the relay selection scheme is proposed for a multiple-relay network. Numerical results are presented in Section V. Finally, Section VI concludes the paper.

II. SYSTEM MODEL

We consider the wireless sensor network shown in Fig. 1, which consists of a antenna source node $\mathcal{S}$, a destination node $\mathcal{D}$, and a battery-enabled relay node $\mathcal{R}$. All nodes in the system model are also equipped with single antennas. The power splitting-based relaying (PSR) protocol in [15] is considered for the AF relay node. We also consider delay-limited transmission, which implies that the received signal is decoded block by block and thus the code length cannot exceed the transmission block time. The relay operates in a half-duplex mode, where the total transmission time T is divided into two halves. In the first phase, $\mathcal{S}$ transmits to both $\mathcal{D}$ and $\mathcal{R}$. A fraction of the received signal at the relay is used for energy harvesting (EH). In the second phase, $\mathcal{R}$ uses the harvested energy to retransmit the received signal to $\mathcal{D}$. The two signals from the source and the relay are combined at the destination node by applying the MRC. We assume independent and identically distributed Rayleigh fading channels h_{sd}, h_{sr} and h_{rd} for $\mathcal{S}$-$\mathcal{D}$, $\mathcal{S}$-$\mathcal{R}$, and $\mathcal{R}$-$\mathcal{D}$ links, respectively. It is assumed that there is perfect channel state information (CSI) for all transmissions known at the destination node.

A. DIRECT TRANSMISSION

In the first phase, the received signal for the $\mathcal{S}$-$\mathcal{D}$ direct link, at $\mathcal{D}$ is given as

$$y_{sd} = \frac{1}{\sqrt{d^{\alpha}}}\sqrt{P_s}h_{sd}s + z_d, \tag{1}$$

where P_s denotes the source transmit power; α is the path loss exponent; d indicates the distance from $\mathcal{S}$ to $\mathcal{D}$; and s is the normalized information signal at $\mathcal{S}$ with $\mathcal{E}[|s|^2] = 1$, where $\mathcal{E}(\cdot)$ stands for the expectation operation. z_d is the zero mean additive white Gaussian noise (AWGN) at $\mathcal{D}$ with variance σ_d^2. From (1), the SNR at the destination node for the direct transmission ρ_{dl} is defined as

$$\rho_{dl} = \frac{P_s|h_{sd}|^2}{d^{\alpha}\sigma_d^2}. \tag{2}$$

B. RELAYING TRANSMISSION

In the first phase, the signal is also transmitted from $\mathcal{S}$ to $\mathcal{R}$. The received signal at the relay node can be expressed as

$$y_{sr} = \frac{1}{\sqrt{d_1^{\alpha}}}\sqrt{P_s}h_{sr}s + z_r, \tag{3}$$

where z_r is the AWGN at the relay node and d_1 indicates the $\mathcal{S}$-$\mathcal{R}$ distance. For the PSR protocol at $\mathcal{R}$, the power splitter separates the received signal in $\beta : 1-\beta$ portions, for energy harvesting, and information amplification and retransmission, respectively, where $0 \le \beta \le 1$ indicates the power splitting (PS) ratio. The harvested energy is obtained as [15]

$$Q = \frac{\zeta\beta P_s|h_{sr}|^2 T}{2d_1^{\alpha}}, \tag{4}$$

where $0 \le \zeta \le 1$ is the energy conversion efficiency. We assume that the energy harvested in this phase is stored in batteries or supercapacitors and used to retransmit the signal.

After PS and down conversion, the received information signal at the relay is represented as

$$y_{sr} = \frac{1}{\sqrt{d_1^{\alpha}}}\sqrt{(1-\beta)P_s}h_{sr}s + \sqrt{(1-\beta)}z_r + z_{cr}, \tag{5}$$

where z_{cr} is the sampled AWGN due to RF band to baseband signal conversion. The relay amplifies the received signal and transmit to the destination in the second phase. The SNR of the $\mathcal{S}$-$\mathcal{R}$ link ρ_{sr} is expressed from (5) as

$$\rho_{sr} = \frac{(1-\beta)P_s|h_{sr}|^2}{d_1^{\alpha}\sigma_R^2}. \tag{6}$$

The received signal at the destination node is given by

$$y_{rd} = \frac{1}{\sqrt{d_2^{\alpha}}}\sqrt{P_r}h_{rd}x + z_d + z_{cd}, \tag{7}$$

where P_r is the transmit power at the relay by applying the harvested energy in the battery, d_2 denotes the $\mathcal{R}$-$\mathcal{D}$ distance, x represents the transmitted signal from the $\mathcal{R}$, with $\mathcal{E}[|x|^2] = 1$, and z_d and z_{cd} are the antenna and conversion AWGNs at the destination node, respectively. For the case where the relay node is equipped with a battery, it is able to utilize the average energy harvested under various channel conditions over a period of time. In this case, the transmit power at the relay node, P_r, is computed by the expected value of the harvested energy Q, in (4) i.e.,

$$P_r = \frac{\mathcal{E}[Q]}{T/2} = \frac{\zeta\beta P_s}{d_1^{\alpha}}, \tag{8}$$

with $\mathcal{E}[|h_{sr}|^2] = 1$, where $\sigma_R^2 = (1-\beta)\sigma_r^2 + \sigma_{cr}^2$. Substituting the (8) into (7), the SNR of the $\mathcal{R}$-$\mathcal{D}$ link ρ_{rd} is written as

$$\rho_{rd} = \frac{\zeta\beta P_s|h_{rd}|^2}{d_1^{\alpha}d_2^{\alpha}\sigma_D^2}, \tag{9}$$

where $\sigma_D^2 = \sigma_d^2 + \sigma_{cd}^2$.

III. OUTAGE PROBABILITY ANALYSIS

In this section, we evaluate the outage probability of the proposed relaying protocol for the direct link, relay and MRC output. The outage probability is defined as the probability that the instantaneous SNR at the receiver output does not exceed a certain predefined threshold SNR. For a fixed source transmission rate, R bits/sec/Hz, the SNR threshold at the destination node is expressed as $\rho_0 = 2^{2R} - 1$.

A. DIRECT LINK

Since $|h_{sd}|^2$ is exponentially distributed with $\mathcal{E}[|h_{sd}|^2] = 1$, ρ_{dl} in (2) is also exponentially distributed with parameter $\lambda_{dl} = \frac{d^{\alpha}\sigma_d^2}{P_s}$. With a minimum acceptable SNR threshold ρ_0, the outage probability of the direct link P_{out}^{dl} is given by

$$\begin{aligned} P_{out}^{dl} &= P\left(\rho_{dl} < \rho_0\right) \\ &= P\left(\frac{P_s|h_{sd}|^2}{d^{\alpha}\sigma_d^2} < \rho_0\right) \\ &= P\left(|h_{sd}|^2 < \frac{\rho_0 d^{\alpha}\sigma_d^2}{P_s}\right). \end{aligned} \tag{10}$$

From (10), the outage probability is obtained from the cumulative distribution function (CDF) of the exponential distribution as follows:

$$P_{out}^{dl} = 1 - \exp\left(-\frac{\rho_0 d^{\alpha}\sigma_d^2}{P_s}\right). \tag{11}$$

B. BATTERY-ENABLED RELAY LINK

From (6) and (9), the instantaneous SNR at the destination for $\mathcal{S}$-$\mathcal{R}$-$\mathcal{D}$ communication, ρ_{srd}, is expressed as

$$\rho_{srd} = \frac{\rho_{sr}\rho_{rd}}{\rho_{sr} + \rho_{rd} + 1} \tag{12}$$

The CDF of a random variable of the form in (12) has been extensively studied in the literature [19], [20]. The CDF of ρ_{srd} is given in the following lemma.

Lemma 1: When x and y are two independent exponential random variables (RV) with parameters $\lambda_x > 0$ and $\lambda_y > 0$, the CDF of the RV $z = \frac{xy}{x+y+1}$ is expressed as

$$P(\mathbf{z} < z) = 1 - e^{-(\lambda_x+\lambda_y)z}\sqrt{4\lambda_x\lambda_y z(z+1)} \times K_1(\sqrt{4\lambda_x\lambda_y z(z+1)}), \quad (13)$$

where $K_1(\cdot)$ is the first-order modified Bessel function of the second kind [21]. The detailed proof is shown in [19].

Since ρ_{sr} and ρ_{rd} are exponentially distributed with parameters $\lambda_{sr} = \frac{d_1^\alpha \sigma_R^2}{(1-\beta)P_s}$ and $\lambda_{rd} = \frac{d_1^\alpha d_2^\alpha \sigma_D^2}{\zeta\beta P_s}$, respectively [19], the outage probability of the destination P_{out} is written as

$$\begin{aligned} P_{out} &= P(\rho_{srd} < \rho_0) \\ &= 1 - e^{-(\lambda_{sr}+\lambda_{rd})\rho_0} u K_1(u) \end{aligned} \quad (14)$$

where $u = \sqrt{4\lambda_{sr}\lambda_{rd}\rho_0(\rho_0+1)}$.

C. MRC OUTPUT

The MRC of the direct and the relay links is applied at $\mathcal{D}$ to maximize the output SNR. The output SNR is expressed as the sum of the SNRs of the individual links, i.e.

$$\rho_{out}^{mrc} = \rho_{srd} + \rho_{dl}. \quad (15)$$

The outage probability of the MRC can be expressed as

$$\begin{aligned} P_{out}^{mrc} &= P\left(\rho_{out}^{mrc} + \rho_{dl} < \rho_0\right) \\ &= P\left(\underbrace{\frac{\rho_{sr}\rho_{rd}}{\rho_{sr}+\rho_{rd}+1}}_{X} + \underbrace{\rho_{dl}}_{Y} < \rho_0\right) \\ &= P(X+Y < \rho_0) \\ &= \int_0^{\rho_0}\int_0^{\rho_0 - x} f_Y(y)\cdot f_X(x)dydx \\ &= 1 - e^{-\lambda_{sd}\rho_0} - \lambda_{sd}e^{-\lambda_{sd}\rho_0} \\ &\quad \times \int_0^{\rho_0} e^{-(\lambda_{sr}+\lambda_{rd}-\lambda_{sd})x}\sqrt{4\lambda_{sr}\lambda_{rd}x(x+1)} \\ &\quad \times K_1(\sqrt{4\lambda_{sr}\lambda_{rd}x(x+1)}) \end{aligned} \quad (16)$$

where the last equality follows from the fact that RV X and Y are exponentially distributed and $\int \exp\left(-\frac{p}{4x} - qx\right)dx = \sqrt{\frac{p}{q}}K_1(\sqrt{pq})$ [21]. At high SNR and a low or moderate transmission rate, (16) can be simplified as

$$P_{out}^{mrc} = 1 - \frac{\lambda_{srd}e^{-\lambda_{sd}\rho_0} - \lambda_{sd}e^{-\lambda_{srd}\rho_0}}{\lambda_{srd} - \lambda_{sd}} \quad (17)$$

where $\lambda_{srd} = \lambda_{sr} + \lambda_{rd}$. Also we assume that $K_1(x) = \frac{1}{x}$ at high SNR.

D. DIVERSITY ANALYSIS

The diversity gain, in general, is defined as the error rate slope as a function of the SNR on a log-log scale. Considering the Taylor series expansion of $e^{\alpha\rho_0}$ as $\rho_0 \to 0$, the outage probability of the relay can be approximated as

$$\begin{aligned} P_{out}^{mrc} &= \lim_{\rho_0 \to 0} 1 - \frac{\lambda_{srd}e^{-\lambda_{sd}\rho_0} - \lambda_{sd}e^{-\lambda_{srd}\rho_0}}{\lambda_{srd} - \lambda_{sd}} \\ &= \frac{1}{2}\lambda_{sd}\lambda_{srd}\rho_0^2. \end{aligned} \quad (18)$$

Based on the concept of information outage probability, the diversity order is defined as

$$g_d = -\lim_{SNR \to \infty}\frac{\log P_{out}^{mrc}}{\log(SNR)}. \quad (19)$$

The power '2' in (18) shows that a diversity order of 2 is obtained for the proposed cooperative relay network. One of the orders is provided by the direct link and the other one by the relay link. Without the direct link, it has been shown that the relay link achieves a diversity order 1. Hence, the direct link improves the outage performance of the proposed relay network. Also, the diversity order is shown to be independent of EH efficiency, since same order is achieved by a non energy harvesting system [1].

E. OPTIMAL POWER SPLITTING RATIO

The optimal value of the PS ratio β can be obtained analytically from the high SNR approximation in (18), and the solution is presented in the following Lemma.

Lemma 2: For the AF relaying system considered in this paper, the PS ratio, β_{opt}, is expressed from (18) as

$$\beta_{opt} = \frac{d_2^\alpha\sigma_D^2 - \sqrt{\zeta d_2^\alpha \sigma_R^2\sigma_D^2}}{d_2^\alpha\sigma_D^2 - \zeta\sigma_R^2}. \quad (20)$$

Proof: See Appendix. Lemma 2 shows that the optimal PS ratio β_{opt} depends only on the distance d_2, which can be easily calculated.

IV. MULTIPLE RELAY WITH RELAY SELECTION

In this section, we propose a multiple relay cooperative network with relay selection based on our derived closed-form expression for outage probability described in Section III. We now consider a model with a source node, a destination node and K relay nodes. With the availability of CSI, the destination node estimates the end-to-end outage probability of each of the K relays. As a result, one relay is selected among the K relays to forward the source signal to the destination. For the i-th relay node, $i = 1, \ldots, K$, the outage probability at the destination node, $P_{out,i}^{mrc}$ is evaluated as in (17). A sub-optimal relay selection method based on distances between nodes is also discusses in this section.

A. MINMAX RELAY SELECTION

From Fig.2(a), for MinMax relay selection scheme, the selection of the optimal relay is only based on the relative distances between the $\mathcal{S}$-$\mathcal{R}_i$ and $\mathcal{R}_i$-$\mathcal{D}$, $d_{1,i}$ and $d_{2,i}$ respectively. For each relay the maximum of $d_{1,i}$ and $d_{2,i}$ is evaluated, i.e.

$$d_i^* = \underset{i}{\operatorname{argmax}}\{d_{1,i}, d_{2,i}\}. \quad (21)$$

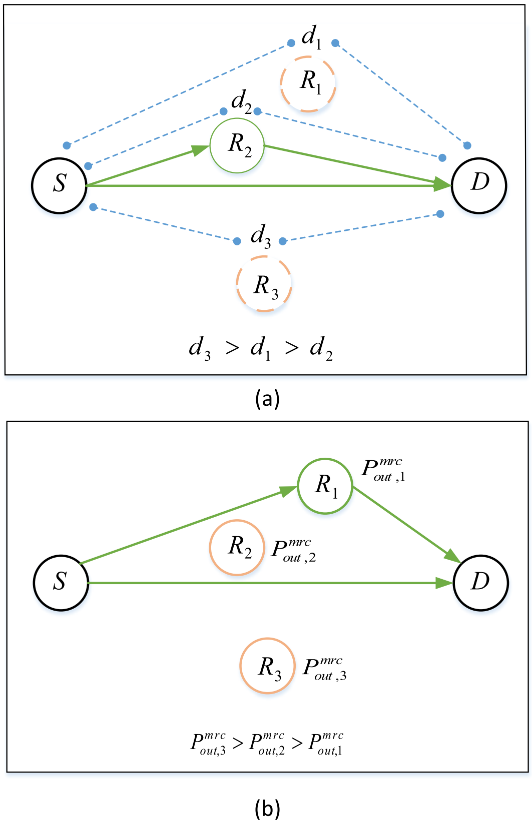

FIGURE 2. Relay selection protocols: (a) MinMax scheme, where the relay with minimum distance is selected, and (b) Optimal relay selection in which the relay with the minimum outage is selected.

The optimal relay is chosen such that d_i^* is minimized, i.e.

$$i^*_{opt} = \underset{i}{\operatorname{argmin}}\{d_i^*\}. \tag{22}$$

B. OPTIMAL RELAY SELECTION

In the optimal relay selection scheme shown in Fig.(2(b)), the selection process is based on the outage probability of the MRC output for each relay. The best relay is selected to minimize the MRC outage probability, i.e.

$$i_{opt} = \underset{i}{\operatorname{argmin}}\{P^{mrc}_{out,i}\}, \tag{23}$$

V. SIMULATION RESULTS

In this section, we provide simulation results to demonstrate the performance of the cooperative communication network with SWIPT. In our simulations, we assume a minimum acceptable transmission rate, $R = 2$ bits/sec/Hz, the pathloss exponent of $\alpha = 2.7$, and energy harvesting efficiency of $\eta = 0.7$. A topology where the relay is located on a straight line between the source and destination is considered, i.e. $d_1 = d - d_2$. The distance between source and destination, d, is normalized to unity.

Fig. 3 shows how the outage probability behaves with increasing transmit power P_s for the single relay scenario. For the purposes of comparison, we plot the scenario with a non-battery (N-B) relay as presented in [17]. It can be observed from Fig. 3 that the outage performance of the relay link with energy harvesting is better than that of the direct link transmission. At a high transmit power of 20dB, the B-E and N-B schemes surpass the direct link transmission by factors of 3 and 2.5 times with respect to MRC respectively, and by a factor of 0.8 and 0.3 times considering only relay transmissions, respectively. It is seen, as expected, that the MRC output outperforms both the direct and cooperative transmissions with a diversity gain of 2. Also, it is shown that the performance of the B-E relay is better than that of the N-B relay by a factor of about 20% at a high transmit power of 40dB. The 20% improvement in performance gain by the B-E over the N-B can be seen for both cases of MRC and relay transmission. This is expected since the relay with battery can save harvested energy for use during a future transmission. Moreover, the results obtained using the closed-form expressions developed in this paper are almost identical

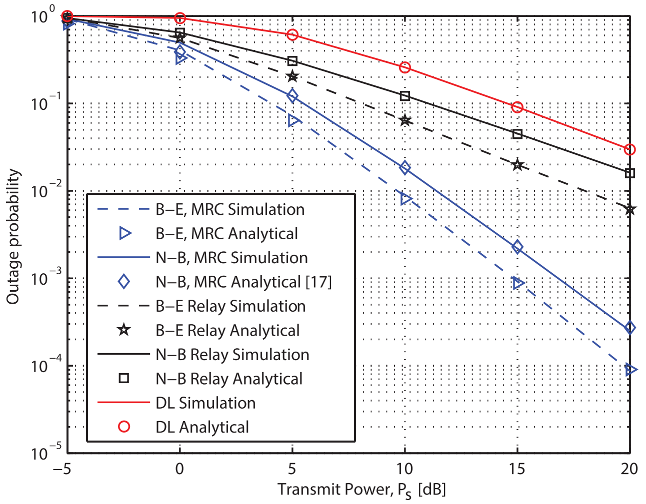

FIGURE 3. Outage probability of cooperative network with respect to transmit SNR for both B-E and N-B relays.

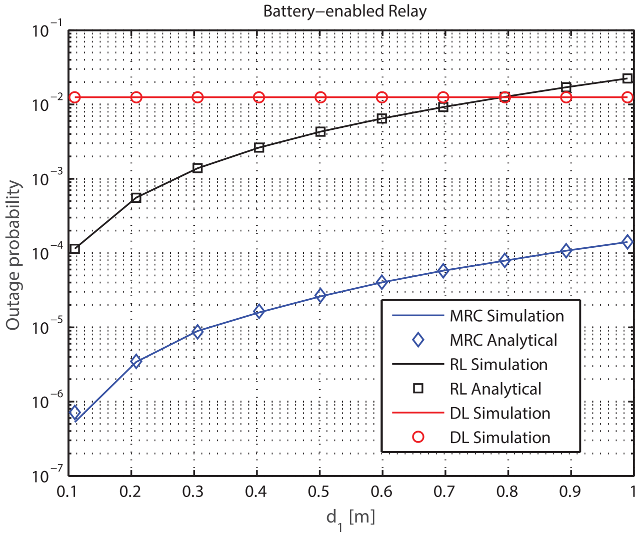

FIGURE 4. Outage probability with respect to source to relay distance, d_1, for B-E relays.

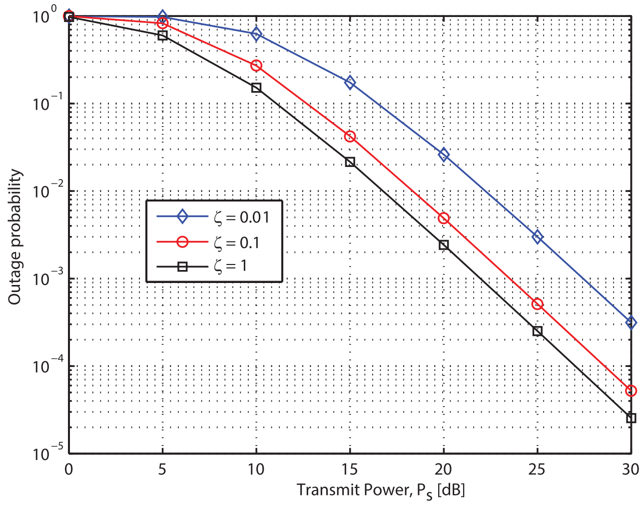

FIGURE 5. Outage probability of MRC output with respect to transmit SNR for different values of ζ.

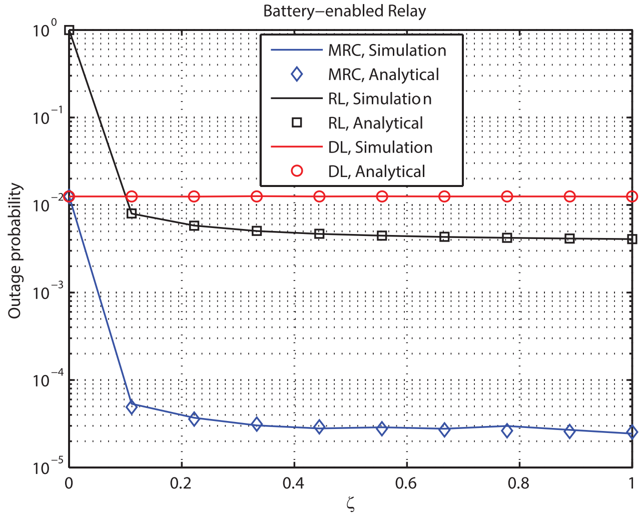

FIGURE 6. Outage probability with respect to energy harvesting efficiency, ζ, for B-E relays.

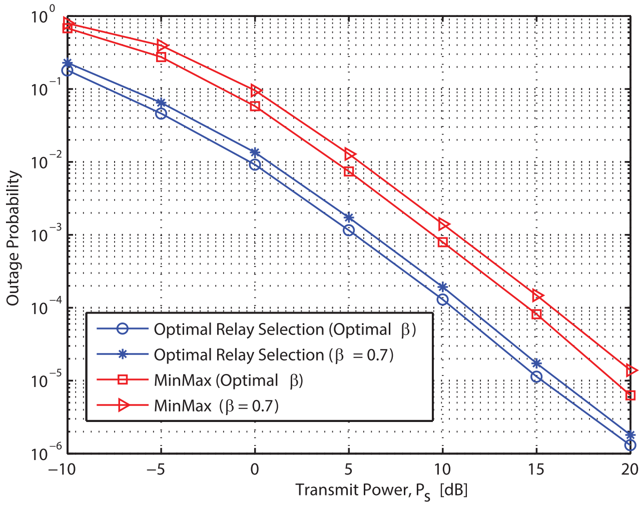

FIGURE 7. Outage probability for relay selection with respect to transmit SNR.

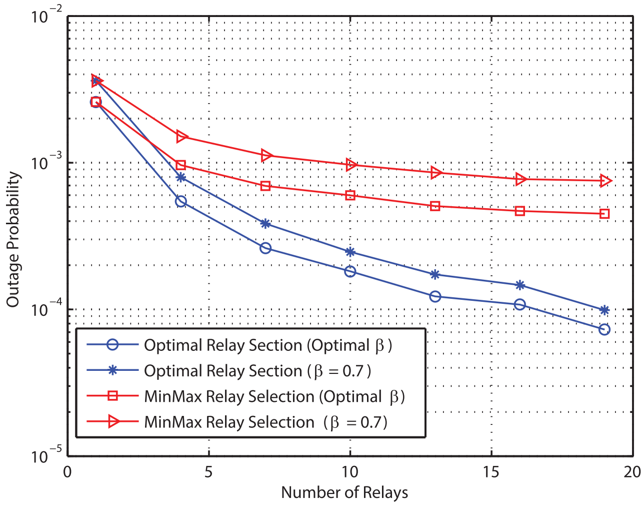

FIGURE 8. Outage probability for relay selection with respect to number of relays.

to the Monte-Carlo simulation, which confirms the accuracy of our analysis. All the considered schemes achieve similar output at low transmit power at the source.

In Fig. 4, we present the outage probability as function of $\mathcal{S}$-$\mathcal{R}$ distance d_1 for the B-E relay with transmit power of 30dB. It can be seen from Fig. 4 that the outage probability of the relay network increases as d_1 increases. A constant margin gain of about 2 exists between B-E MRC and relay transmission scenarios with increasing distance, d_1. This is because by increasing d_1, both energy harvested and the received signal strength at the relay node decrease due to large path lose, d_1^{α}. It is also shown that the analytical results achieves identical performance as the numerical simulation with lower computational complexity from the Monte Carlo simulation.

Fig. 5 shows the outage probability versus transmit power, P_s for the B-E MRC output with different values of energy harvesting efficiency ζ. It can be seen from Fig. 5 that the diversity order of the MRC output is independent of the value of ζ. This shows that the randomness of the harvested power does not have any effect on the diversity gain. Also, with an increase in ζ, the performance MRC scheme improves by margins of 1 and 0.2 for $\zeta = 0.01$ and $\zeta = 0.1$ respectively compared with $\zeta = 1$. This behavior implies that with better energy harvesting efficiency, the energy harvesting nodes improve in performance. This behavior is also confirmed from Fig. 6. Fig. 6 plots the outage probability against ζ (i.e $0 \leq \zeta \leq 1$) at 30dB for B-E scenario. It can be observed from Fig. 6 that ζ has no effect on the direct link transmission. For both the relay link and MRC output, the outage probability decreases asymptotically with ζ.

In Figs. 7 and 8, we show the performance analysis of our relay selection schemes in a simulation environment. For comparison with our optimal power splitting ratio β_{opt}, the power splitting ratio, β is fixed to study its effect on the relay selection schemes performances. Fig. 7 depicts the outage probability of both the optimal and MinMax relay selection versus the transmit power, P_s with $K = 20$. The optimal relay selection outperforms the MinMax as expected with a performance gain of 1. The direct link transmission is unaffected by ζ because energy harvesting does not occur at all direct link participating nodes. The outage probability performance with respect to the number of relays is shown in Fig. 8 for a transmit power SNR of 10dB. It can be seen that, increasing the number of relay nodes improves the outage performance. Both figures show that the use of the optimal power ratio β_{opt} achieves better performance compared to a fixed value of β.

VI. CONCLUSION

In this paper, we have investigated an amplify-and-forward cooperative communication network based on the PSR protocol. An MRC method was employed at the destination node. The analytic expression for the outage probability was derived in the delay-limited transmission mode, for B-E relays. Simulation results show that the MRC achieves a better performance than both direct and relay transmissions. We also extended our system model to the multiple relay scenario where the best relay is selected in each time instance to forward the source signal to the destination. The system performance is shown to improve by implementing relay nodes with battery.

APPENDIX
PROOF OF THE OPTIMAL VALUE FOR POWER SPLITTING RATIO

This appendix proves the optimal value of the power splitting ratio, β. From the Taylor series approximation in (18), we have

$$\begin{aligned} P_{out} &= \nu(\lambda_{sr} + \lambda_{rd}) \\ &= \nu\left(\frac{d_1^\alpha \sigma_R^2}{(1-\beta)P_s} + \frac{d_1^\alpha d_2^\alpha \sigma_D^2}{\zeta \beta P_s}\right) \end{aligned} \tag{24}$$

where $\nu = \frac{1}{2}\lambda_{sd}\rho_0^2$.

For an expression of this form, the optimal value is evaluated as

$$\begin{aligned} \underset{x\in(0,1)}{\arg\max}\left(\frac{A}{x} + \frac{B}{1-x}\right) &= \frac{\sqrt{A}}{\sqrt{A}+\sqrt{B}} \\ &= \frac{A-\sqrt{AB}}{A-B}. \end{aligned} \tag{25}$$

Therefore, the optimal power splitting ratio is evaluated from (24) as

$$\beta_{opt} = \underset{\beta\in(0,1)}{\arg\min}\left(\frac{A}{\beta} + \frac{B}{1-\beta}\right) \tag{26}$$

where $A = \frac{d_1^\alpha d_2^\alpha \sigma_D^2}{\zeta P_s}$ and $B = \frac{d_1^\alpha \sigma_R^2}{P_s}$. Substituting A and B into (25) the optimal value of β is given by

$$\beta_{opt} = \frac{d_2^\alpha \sigma_D^2 - \sqrt{\zeta d_2^\alpha \sigma_R^2 \sigma_D^2}}{d_2^\alpha \sigma_D^2 - \zeta \sigma_R^2}. \tag{27}$$

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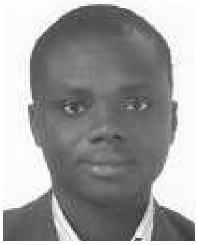
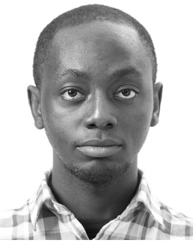
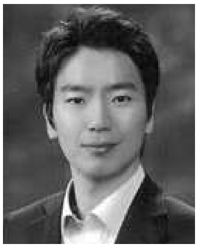


SUMAILA MAHAMA received the B.Sc. degree in telecommunications engineering from the Kwame Nkrumah University of Science and Technology, Ghana, in 2013, the M.S. degree in electronic engineering from Hanbat National University, South Korea, in 2016, where he is currently pursuing the Ph.D. degree with the Department of Electronic Engineering.



DEREK KWAKU POBI ASIEDU received the B.Sc. degree in biomedical engineering from the University of Ghana (UG), Ghana, in 2011, the M.S. degree in computer engineering from the Department of Computer Engineering, UG, and the M.S. degree in electronic engineering from Hanbat National University, South Korea, in 2017, where he is currently pursuing the Ph.D. degree with the Department of Electronic Engineering.



KYOUNG-JAE LEE (S'06–M'11) received the B.S., M.S., and Ph.D. degrees from the School of Electrical Engineering, Korea University, Seoul, South Korea, in 2005, 2007, and 2011, respectively. During 2006, he interned at Beceem Communications, Inc., Santa Clara, CA, USA, and during 2009, he visited the University of Southern California, Los Angeles, CA, as a Visiting Student. He was a Research Professor with Korea University in 2011. From 2011 to 2012, he was a Post-Doctoral Fellow at the Wireless Networking and Communications Group, University of Texas at Austin, Austin, TX, USA. Since 2012, he has been with the Department of Electronics and Control Engineering, Hanbat National University, Daejeon, South Korea, where he is currently an Associate Professor. His research interests are in communication theory, signal processing, and information theory applied to the next-generation wireless communications. He was a recipient of the Best Paper Award at the IEEE VTC Fall in 2009, the IEEE ComSoc APB Outstanding Paper Award in 2013, and the IEEE ComSoc APB Outstanding Young Researcher in 2013.

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