Energy Harvesting with Link Adaptation under Different Wireless Relaying Schemes

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Abstract —This paper investigates the performance of Energy Harvesting (EH) relaying with link adaptation for two combining schemes based on amplify-and-forward relaying systems. The first scheme defined as All Relay Participate (ARP), where the destination combines the received signals from all the relays, while the second scheme is known as Best Relay Selection (BRS) scheme, which used the relay that has the maximum Signal to Noise Ratio (SNR) at the destination. To simplify comparisons between the two schemes, total Probability Density Function (PDF) and moment generating function (MGF) for each scheme are derived and the spectral efficiency (SE) with link adaptation is presented. The trade-off between performance and complexity is compared by using the average number of active relays that participate in the cooperative diversity and Cumulative Distribution Function (CDF) of the link adaptation. The results show that the wireless EH relay performance at its maximum when utilize ARP scheme rather than BRS. However, the link adaptation performance is achieved at the expense of degradation in the spectral efficiency. In terms of practicality, the simulation results shown that the BRS performs better than ARP, since BRS requires a small number of active relay implementation for the wireless EH relay system.

Index Terms—Energy harvesting relaying, spectral efficiency, adaptive modulation, all relay participate, best relay selection

I. INTRODUCTION

Radio Frequency (RF) signals that radiate from adjacent transmitters recently has been considered as an alternative source for Energy Harvesting (EH). From the RF signals, the information and the energy can be simultaneously carried. Consequently, the effective resource can be allocated from the transceiver designs via a technique known as Simultaneous Wireless Information and Power Transfer (SWIPT) [1]. SWIPT is employed in solving practical issues regarding interference alignment. SWIPT also has been considered as a potential technology to be used within 5G networks to address the limited power challenge for future smart devices.

Cooperative Relaying (CR) is considered as the essential development in wireless communication that is employed in achieving energy-efficient transmission to mitigate fading [2]. There are two major relaying schemes from the CR technique, which are; (i) decode and forward (DF) and (ii) amplify and forward (AF). Employing CR technique within wireless network suffers different challenges in comparison with the direct transmissions, such as; throughput loss. This loss occurred due to the usage of additional relaying resources [3]. Consequently, the researchers introduced several methods to improve the performance and address the problem of throughput loss.

Link adaptation, by using adaptive modulation (AM) approach is exploited within the wireless systems via selecting the suitable type of modulation and constellation size based on the received SNR. In AM, the SNR gain is transformed into throughput [4]. Both AM and CR are employed to achieve the 5G network requirements. The limited battery life to power up the relays is another challenge in CR, which in turns results in a short lifetime for the network [5]. Conventional sources of EH, such as; thermal, solar and wind are not available all the time due to their nature and seasonality, which in turns reduces the wireless network reliability. Moreover, these sources cannot be re-charged for certain applications. The demand to move towards alternative energy sources is driven by the effort to reduce the energy consumption in future green radio networks [6]. The green radio networks aim to compensate for the increase in total energy consumption, carbon footprint, and operational cost as a result from the increase in the number of base stations (BSs), which consume 57% of the total mobile network infrastructure energy [7]. Another alternative power source from the wireless transmission can be exploited by the use of near-field wireless power transfer (WPT), as presented in [8].

The focus of this study is on employing RF signals for SWIPT as an alternative EH source; due to the ability to carry information and energy simultaneously [9].

The remainder of the paper is organized as follows. Section II discusses recent developments and a critical review of the previous studies. Section III describes the proposed system of EH relaying and channel models for ARP and BRS schemes. In Section IV, the performance of SE and an average number of active relays for cooperative EH relaying of different cases are presented for ARP and BRS schemes. Comparison results are presented in Section V, while Section VI concludes this research works.

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II. Related works & Research Contributions

In [10], SWIPT within two-hop relay system was evaluated. The authors generated the associated optimization problems for power splitting ratios in addition to the optimal solutions for both DF and AF protocols.

In [11], two schemes were presented for power transfer and wireless information, which are; time switching (TS) and power splitting (PS). In PS scheme, the receiver divides the signal power for information decoding and energy harvesting. In TS scheme, the receiver switches between information decoding and energy harvesting.

Authors in [12] investigated TS protocol within multiple relays network for EH and beamforming schemes. In [13], interference analysis for EH based on PS and TS schemes were proposed. Authors in [11] investigated the problem of AM within DF systems considering limited channel state information (CSI) for the link between source and relay.

In [15], the authors derived new expressions for the PDF and the CDF of SNR for opportunistic AF relaying network with dual hops. Relay selection was also adopted, where SNR policy was considered depending on the obtainable CSI. The results confirmed the effectiveness of the model for a different number of candidate relays and various fading distributions. They also compared the performance of their system to the performance of the dual-hop system without using relay selection and to dual-hop system considering maximum SNR between relay and destination for selecting the relay. The results illustrated that their proposed selection method outperforms the other two considered cooperative schemes.

In [16], the authors introduced CA schemes to overcome the issue of the dense area due to plenty of antenna elements within the small mobile terminal size. Link adaption is also considered as a critical communication technique to improve the SE. In their work, the efficiency of rate adaptive and constant-power M-QAM transmission technique in AF cooperative networks was compared and investigated.

Authors in [17] stated that cooperative communication technique was introduced and developed to improve the capacity of the system and increase the diversity gain within wireless networks without using additional resources. They derived expressions to obtain closed-form expressions for CDF and PDF for end-to-end SNR of the opportunistic relaying system with relay selection based on maximum end-to-end SNR. They employed these expressions in finding exact solutions for the integral of average SEP, ergodic capacity and the outage probability of the considered cooperative communication system.

In [18], the performance of Incremental Hop Selection (IHS) scheme within the cooperative network was analyzed. In general, the communication networks of multiple relays suffer a loss in SE because of multiple time-phases usages. This problem can be prevented by IHS scheme since the number of hops is increased only when the target performance cannot be supported by current path. Furthermore, the authors used AM technique with IHS scheme to increase the SE without affecting the target performance. They derived closed-form expressions for the coding and diversity gains in addition to evaluate the SE and the OP performances.

In [19], researchers proposed an interference-aided energy harvesting model for cooperative relaying systems, in which the energy is harvested from both the co-channel interference and received information signals by energy-constrained relays. Such energy was deployed to send the properly decoded signal to the target destination. Both the TS and PS models were adopted in the proposed work. The analytical formulae concerning the ergodic and outage capacities of the application of such an EH technique in a decode-and-forward relaying system were derived. Results revealed that the PS model outperformed the TS in terms of SNR and throughput. In addition, the related system capacity relation was obtained, considering various interference power distributions.

In [20], spectral efficiency is studied over single energy harvesting AF-relay with link adaptation technique. The study shows that energy harvesting relaying is optimized and compared with the conventional cooperative relaying. Results shown that the performance of next green cooperative systems compared with conventional cooperative relaying ones. The simulation demonstrates that using green cooperative systems degrades the spectral efficiency by only 5%.

In this study, EH relaying and link adaptation are used over AF protocol. Two cooperative relaying schemes are considered: All Relay Participate (ARP) and Best Relay Selection (BRS). The contributions of this study can be summarized as follows:

i.) The mathematical derivation of the combined PDF and MGF for both ARP and BRS schemes.
ii.) The effect of the link adaptation, by using adaptive modulation on the spectral efficiency for both schemes, by analyzing the CDF for each scheme.
iii.) The trade-off between performance and complexity for both ARP and BRS schemes with conventional and EH relay systems.

III. System Model

We consider a downlink EH relaying, where a source node S communicate with a destination node D with the help of EH relaying R_i, $i \in \{1,2,\ldots,N\}$ with PS protocol. Assuming the direct path between S and D with SNR, γ_{SD}, with channel coefficients, h_{sd}. On the other hand, the SNR between S and R_i is denoted by $\gamma_{si} = |h_{si}|^2 E_s/N_o$ with channel coefficients h_{si}. The SNR between R_i and D is denoted by $\gamma_{id} = |h_{id}|^2 E_s/N_o$ with channel coefficients h_{id}. All nodes are assumed with a single antenna and all nodes operate in a half-duplex mode. All links are assumed to undergo independent Rayleigh fading channel with perfect CSI.

Each relay, *i*, assumed a harvest portion of the received signal by power splitting protocol. A portion of the received signal to each relay is divided for information decoding by a value of α_i. Thus, the rest of the signal will be represented by $1-\alpha_i$ as shown in Fig. 1.a. where T is the block time. The cooperative EH relaying system model is shown in Fig. 1.b that represents ARP scheme, while Fig. 1.c represents BRS scheme.

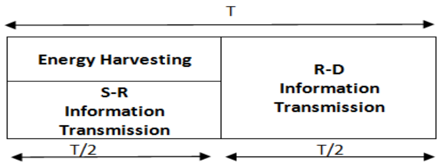

Fig. 1.a: Time frame structure for power splitting

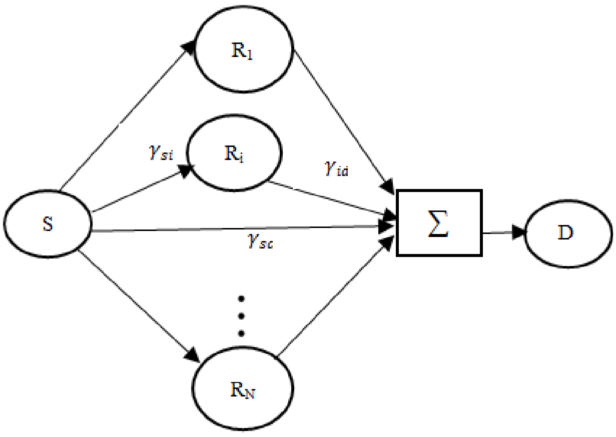

Fig 1.b: Downlink EH relaying with ARP scheme

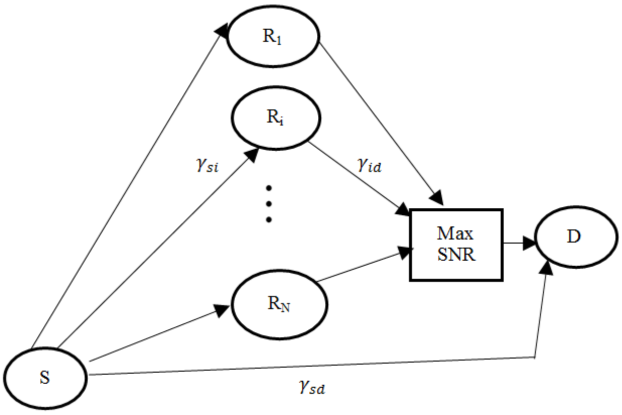

Fig. 1.c: Downlink EH relaying with BRS scheme

In this paper, QPSK, 16-QAM and 64-QAM are considered for link adaptation according to Long Term Evolution-Advanced (LTE-A) standards [21]. Target bit error rate assumed to be 10^{-5} to be suitable for the modulation mode and Quality of Service (QoS) requirements for 4G network and beyond. SNR values can be divided considering *M+1* regions, where *M* is a number of thresholds of SNR values. The thresholds can be found using [22]:

$$\gamma_m = \frac{2}{3}K_0(2^m - 1) \quad m = 2,4,6 \tag{1}$$

where, $erfc^{-1}(.)$ represents the inverse complementary error function. Also, $\gamma_{M+1} = \infty$, $k_0 = -In\,(5\,BERT)$, where *BERT* is the target bit error rate.

In the case of cooperative energy harvesting, the received signal at the relay *i*, can be written as:

$$y_{SR}^i = \sqrt{P_s} h_{si} s + n_{SR} \tag{2}$$

where $n_{SR} \sim CN(0, \sigma_{SR}^2)$ is AWGN with noise variance σ_{SR}^2. In this paper, dynamic power splitting ratio is used, so each relay harvest a different portion of the received signal. Assuming PS scheme, $\sqrt{\alpha_i} y_{SR}^i$ is used for energy harvesting to relay *i*, where the remaining $\sqrt{1-\alpha_i} y_{SR}^i$ is used for information detection for relay *i*. The harvested energy at relay *i*, at time $\frac{T}{2}$, where T is the block time can be presented as follow:

$$E^i = \zeta \alpha_i P_s |h_{si}|^2 . \left({}^{T}\!/_{2}\right) \tag{3}$$

where ζ is the energy conversion efficiency. After power splitting, at the input of the energy harvester and after power splitting, the received signal can be written as:

$$R^i = \sqrt{1-\alpha_i}\left(\sqrt{P_s} h_{si} s + n_{SR}\right) + \dot{n}_{SR} \tag{4}$$

where $\dot{n}_{SR} \sim CN(0, \dot{\sigma}_{SR}^2)$ is AWGN from information receiver. In the second time slot, the transmitted power of the relay *i* is given by:

$$P_R^i = \frac{E^i}{T/2} = \zeta \alpha_i P_s |h_{si}|^2 \tag{5}$$

The relay amplifies the signal and forwards it to the destination, the transmitted signal at the relay can be written as:

$$W^i = \sqrt{P_s P_R^i (1-\alpha_i)} G h_{si} s + \sqrt{P_R^i} G n_W \tag{6}$$

where, $n_W = \sqrt{(1-\alpha_i)} n_{SR} + \dot{n}_{SR}$, G is the gain of relay *i*, we assume fixed gain to all relays, G, which is given as:

$$G = \frac{1}{\sqrt{(1-\alpha_i) P_s {h_{si}}^2 + \sigma_W^2}} \tag{7}$$

The received signal at the destination:

$$y_{RD}^i = h_{id} W^i + n_{RD} \tag{8}$$

After substituting (6) and (7) into (8), the end-to-end SNR can be written as:

$$\gamma_{tot} = \frac{\zeta\alpha(1-\alpha)\bar{\gamma}}{\zeta\alpha + \zeta\alpha(1-\alpha) + (1-\alpha)} \tag{9}$$

assuming $\dot{\sigma}_{SR}^2 = \sigma_{SR}^2, \sigma_{RD}^2 = \sigma_{SD}^2, \mathbb{E}\{|h_{si}|^2\} = \mathbb{E}\{|h_{id}|^2\} = 1$.

A. All Relay Participate (ARP)

In the case of ARP scheme, the combined signals at the destination for *N*-relays can be computed, where total SNR can be shown as [23], [24]:

$$\gamma_{tot} = \gamma_{SD} + \sum_{i=1}^{N} \frac{\gamma_{si}\ \gamma_{id}}{\gamma_{si} + \ \gamma_{id} + 1} \tag{10}$$

All nodes are assumed with a single antenna and all nodes operate in a half-duplex mode. All links are assumed to undergo Rayleigh fading channel with CSI. For Rayleigh fading channel, the moment generating function (MGF) of the direct path can be computed as:

$$M_{\gamma_{SD}}(s) = \int_0^\infty \frac{1}{\bar{\gamma}_{SD}} \exp\left(\frac{-\gamma}{\bar{\gamma}_{SD}}\right) \exp(-s)\, d\gamma \tag{11}$$

$$M_{\gamma_{SD}}(s) = (1 + \bar{\gamma}_{SD} s)^{-1} \tag{12}$$

In the case of conventional relaying (non-EH), received SNR is independent and identical distribution (i.i.d.) for each path, then we can write the MGF of γ_{tot} as:

$$M_{\gamma_{tot}}(s) = M_{\gamma_{SD}}(s) \prod_{i=1}^{N} M_{\gamma_i}(s) \tag{13}$$

To find $M_{\gamma_i}(s)$, cumulative distribution function (CDF) of γ_i should be computed:

$$P_{\gamma_i}(\gamma) = 1 - \ Prob(\ \gamma_{si} > \gamma) Prob(\ \gamma_{id} > \gamma) \tag{14}$$

where,

$$prob(\ \gamma_{si} > \gamma) = \int_\gamma^\infty \frac{1}{\bar{\gamma}_{si}} \exp\left(\frac{-\gamma}{\bar{\gamma}_{si}}\right) d\gamma = \exp\left(\frac{-\gamma}{\bar{\gamma}_{si}}\right) \tag{15}$$

Assume $\bar{\gamma}_{si} = \bar{\gamma}_{id} = \bar{\gamma}$,

$$P_{\gamma_i}(\gamma) = 1 - \exp\left(\frac{-2\gamma}{\bar{\gamma}}\right) \tag{16}$$

The probability density function (PDF) of γ_i can be computed as:

$$p_{\gamma_i}(\gamma) = \frac{2}{\bar{\gamma}} \exp\left(\frac{-2\gamma}{\bar{\gamma}}\right) \tag{17}$$

and MGF of γ_i can be computed as:

$$M_{\gamma_i}(s) = (1 + 0.5\bar{\gamma}s)^{-1} \tag{18}$$

The combined MGF can be computed as:

$$M_{\gamma_{tot}}(s) = (1 + \bar{\gamma}_{SD} s)^{-1} (1 + 0.5\bar{\gamma}s)^{-N} \tag{19}$$

According to previous equations, in the case of cooperative energy harvesting, (13) can be written as:

$$M_{\gamma_{tot}}(s) = (1 + \bar{\gamma}_{SD} s)^{-1} \prod_{i=1}^{N} (1 + C_i s)^{-1} \tag{20}$$

where C_i is the SNR at relay *i*. After using a partial fraction, the total MGF can be written as:

$$M_{\gamma_{tot}}(s) = R_{SD}(1 + \bar{\gamma}_{SD} s)^{-1} + \sum_{i=1}^{N} R_i (1 + C_i s)^{-1} \tag{21}$$

where

$$R_{SD} = \prod_{i=1}^{N} \left(1 - \frac{C_i}{\bar{\gamma}_{SD}}\right)^{-1} \tag{22}$$

$$R_i = \left(1 - \frac{\bar{\gamma}_{SD}}{C_i}\right)^{-1} \prod_{w=1, w\neq i}^{N} \left(1 - \frac{C_w}{C_i}\right)^{-1} \tag{23}$$

After taking inverse Laplace transform, the total probability density function (PDF) for the ARP scheme can be written as:

$$p_{\gamma_{tot}}(\gamma) = \frac{R_{SD}}{\bar{\gamma}_{SD}} exp\left(\frac{-\gamma}{\bar{\gamma}_{SD}}\right) + \sum_{i=1}^{N} \frac{R_i}{C_i} exp\left(\frac{-\gamma}{C_i}\right) \tag{24}$$

B. Best Relay Selection (BRS)

In the case of conventional relaying, the combined signals at the destination can be computed using BRS scheme, shown as:

$$\gamma_{tot} = \gamma_{SD} + \gamma_r \tag{25}$$

where $\gamma_r = Max_i\left(\frac{\gamma_{si}\gamma_{id}}{\gamma_{si}+\gamma_{id}+1}\right)$, $\gamma_{SD} = |h_{sd}|^2 E_s/N_o$, $\gamma_{si} = |h_{si}|^2 E_s/N_o$ is the instantaneous SNR between *S* and R_i, $\gamma_{id} = |h_{id}|^2 E_s/N_o$ is the instantaneous SNR between R_i and *D*. Also, the MGF can be expressed as:

$$M_{\gamma_{tot}}(s) = M_{\gamma_{SD}}(s) M_{\gamma_r}(s) \tag{26}$$

For Rayleigh fading channel, $M_{SD}(s) = (1 + s\bar{\gamma}_{SD})^{-1}$, while, MGF of γ_r in case of BRS scheme for *m* relays can be expressed as [25, Chapter 9]:

$$M_{\gamma_r}(s) = \sum_{i=0}^{N-1} \frac{N(-1)^i \binom{N-1}{i}}{1 + i + s\bar{\gamma}/2} \tag{27}$$

Thus, (26) can be written in the case of cooperative energy harvesting as:

$$M_{\gamma_{tot}}(s) = (1 + \bar{\gamma}_{SD} s)^{-1} \sum_{i=0}^{N-1} \frac{N(-1)^i \binom{N-1}{i}}{1 + i + s\bar{\gamma}_{EH}/2} \tag{28}$$

using a partial fraction and taking Inverse Laplace transform with some algebraic manipulation, the total PDF for the BRS, γ_{tot} can be expressed as:

$$p_\gamma(\gamma) = N \sum_{i=0}^{N-1} (-1)^i \binom{N-1}{i} \left[\frac{A_i}{\bar{\gamma}_{S,D}} exp\left(-\frac{\gamma}{\bar{\gamma}_{S,D}}\right) + \frac{2B_i}{\bar{\gamma}_{EH}} exp\left(-\frac{2(1+i)\gamma}{\bar{\gamma}_{EH}}\right) \right] \tag{29}$$

where $A_i = \frac{1}{1+i-\frac{\bar{\gamma}_{EH}}{2\bar{\gamma}_{SD}}}$, $B_i = \frac{1}{1-(1+i)\frac{2\bar{\gamma}_{SD}}{\bar{\gamma}_{EH}}}$.

The combined PDF for BRS protocol is derived in Appendix A.

IV. Performance Analysis

A. Spectral Efficiency

The following expression can be used to compute the spectral efficiency with adaptive modulation system, denoted by η:

$$\eta = \frac{1}{2} \sum_{m=2}^{M} log_2{}^{M_m} F_m \tag{30}$$

where F_m represents the probability of selecting the m^{th} modulation model for the transmission. The ½ scaling factor is introduced based on the fact that transmission process of cooperative diversity occurred in two-time slots. This probability can be computed by the difference between the next modulation index and the current modulation index as follows:

$$F_m = P_\gamma(\gamma_{m+1}) - P_\gamma(\gamma_m) \tag{31}$$

where γ_m is the threshold of SNR and $P_\gamma(.)$ is the cumulative distribution function (CDF) of received SNR.

B. Average Number of Active Relays

Increase the number of active relays in the cooperative relaying system will improve the diversity gain. However, that leads to increase in system complexity and power consumption. In this section, the trade-off between performance and complexity between ARP and BRS schemes is evaluated. The active relay occurred if there is an active transmission with the destination, provided that the end-to-end SNR is above the predefined threshold.

In this work, the predefined threshold is equal to γ_2 in (1). Therefore, the average number of active relays can be written as:

$$AR = \begin{cases} N(1-F_2) & , \; ARP \\ 1(1-F_2) & , \; BRS \end{cases} \tag{32}$$

V. Simulation and Numerical Results

Simulation and numerical results from the ARP and BRS schemes are presented in this section. The systems parameters are M=3, $BERT = 10^{-5}$, N = 2, 5, ζ = 0.6.

Fig. 2 show the CDF for two schemes for conventional and EH relaying. As shown, ARP provides better performance than BRS. The degradation of using EH protocol is clearly shown, for example at 15 dB SNR, CDF for ARP scheme is about 0.92 and 0.7 for conventional and EH relaying respectively, while in the case of BRS scheme, it is about 0.88 and 0.55 for conventional and EH relaying respectively. The result shown that loss in BRS is higher than ARP scheme.

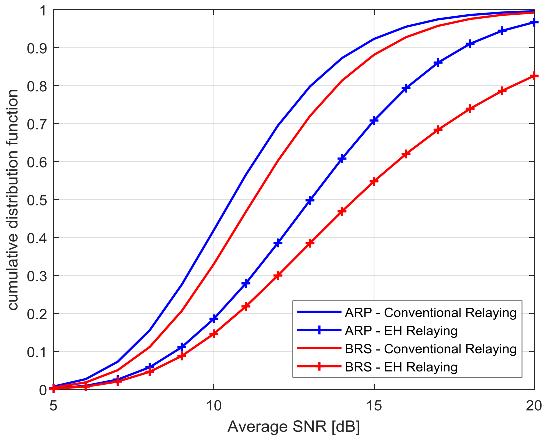

Fig. 2. CDF of conventional and EH relaying for ARP and BRS schemes

Fig. 3 shows the SE for conventional and EH relays for ARP and BRS schemes with N = 2. Cooperative EH relay causes a degradation in the SE compared with the conventional cooperative relay. For example, in the case of ARP scheme, at 20 dB SNR, the SE for the EH relay is 1.7 bits/sec/Hz and that for the conventional relay is approximately 2.1 bits/sec/Hz. Therefore, a 0.4 bits/sec/Hz loss is observed in the EH relay in comparison with the conventional cooperative relay, which translated to a 19% loss in SE. In the case of BRS scheme, at 20 dB SNR, the SE for EH relaying is approximately 1.3 bits/sec/Hz; approximately 0.5 bits/sec/Hz loss is observed compared with conventional cooperative relaying, which translated to a 27% loss in SE.

Fig. 4 represents the SE for ARP and BRS schemes with N = 5. As shown, the performance of the SE enhances with the increase in the number of relays. For example, for ARP scheme, at N = 5, the SE of the conventional and EH relays are 2.6 and 2.2, respectively, which translate to a 20% and 22% improvement in the SE, respectively compared to N = 2. On the other hand, in the case of BRS scheme, for N = 2, the SE of the conventional and EH relays are 1.8 and 1.3, respectively. Meanwhile, for N = 5, the SE of the conventional and EH relays are 2 and 1.5, respectively, which translate to a 10% and 33% improvement in the SE, respectively.

On the other hand, Fig. 5 and 6 represent the complexity of the system by computing the average number of active relays for ARP and BRS schemes for N = 2 and N = 5 respectively. As shown, increasing number of relays leads to increasing number of active relays at low SNR region, since increasing number of relays will enhance the end-to-end SNR. Also, in the case of ARP scheme, it is clear that a number of active relays is proportional with the number of relays, while in the case of BRS scheme, it is clear that number of active relays is not proportional with the number of relays, since only the best relay is used.

Finally, in the case of EH relays, it requires a less average number of active relays compared with conventional relays, this is due that EH relays require a less power consumption compared with conventional relays in low SNR region.

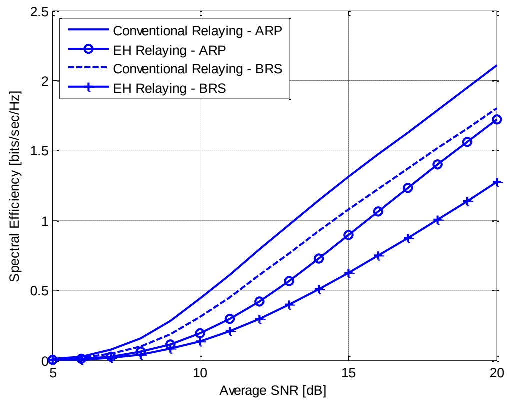

Fig. 3. Spectral efficiency of conventional and EH relaying for ARP and BRS schemes, $N = 2$

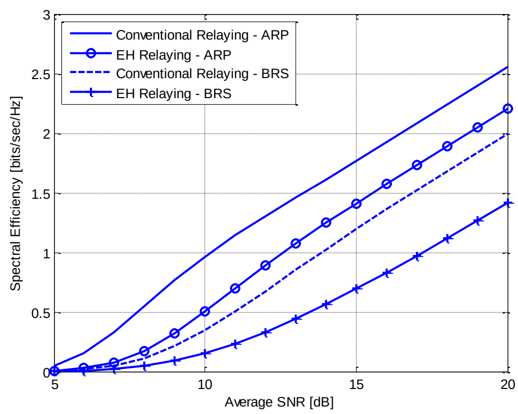

Fig. 4. Spectral Efficiency of conventional and EH relaying for ARP and BRS schemes, $N = 5$

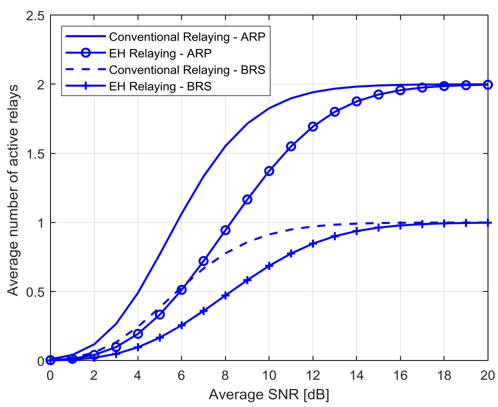

Fig. 5. Average number of active relays of conventional and EH relaying for ARP and BRS schemes, $N = 2$

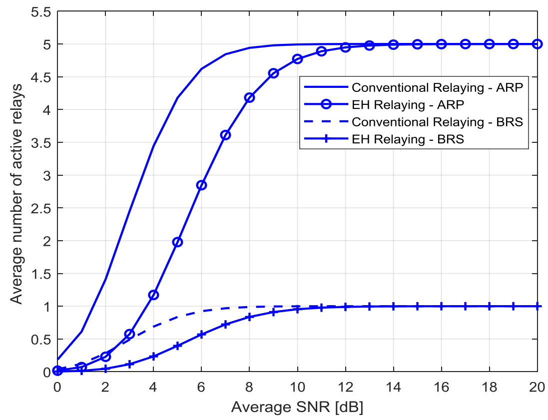

Fig. 6. Average number of active relays of conventional and EH relaying for ARP and BRS schemes, $N = 5$

VI. Concluding Remarks

This paper has investigated two different combining protocols with dual hop AF-EH relaying systems with link adaptation scheme, where a PS relay was adopted.

As opposed to the conventional relay that works without giving any power supply, the EH provides a source of power in relaying networks. The results shown that the performance in SE of ARP protocol is better than BRS protocol for both conventional and EH relaying. A degradation in the SE due to use of EH scheme can be observed. Using the EH degrades the performance of the SE for the ARP protocol to 19%, while the degradation in the SE for the BRS protocol is about 27% for $N = 2$ relays. However, this can be compensated by increasing the number of relays to enhance the SE for both protocols.

Results also shown that BRS scheme offers less implementation complexity compared to ARP, since ARP scheme requires more relays participation to allow more information exchange among the relays, which increases the relay EH system complexity.

As a possible extension of this work, Generalized Selection Combining (GSC) can be considered, since it is shown in previous studies that GSC able to offer a balance between the performance of both ARP and BRS schemes.

Appendix

It is shown in [22, Chapter 9], the moment generating function (MGF) of γ_r can be written as (27). Therefore, (28) can be written as

$$M_{\gamma_{tot}}(s) = N \sum_{i=0}^{N-1} (-1)^i \binom{N-1}{i} F_i(s) \tag{33}$$

where

$$F_i(s) = \frac{1}{\left(1 + s\bar{\gamma}_{S,D}\right)\left(1 + i + s\frac{\bar{\gamma}_{EH}}{2}\right)} \tag{34}$$

Next, we can transform expression (34) to

$$F_i(s) = \frac{A_i}{1 + s\bar{\gamma}_{S,D}} + \frac{B_i}{1 + i + s\frac{\bar{\gamma}_{EH}}{2}} \quad (35)$$

where

$$A_i = \frac{1}{1 + i - \frac{\bar{\gamma}_{EH}}{2\bar{\gamma}_{S,D}}} \quad (36)$$

$$B_i = \frac{1}{1 - (1 + i)\frac{2\bar{\gamma}_{S,D}}{\bar{\gamma}_{EH}}} \quad (37)$$

Substituting (35) into (33), we obtain

$$M_{\gamma_{tot}}(s) = N \sum_{i=0}^{N-1} (-1)^i \binom{N-1}{i} \left[\frac{A_i}{1 + s\bar{\gamma}_{S,D}} + \frac{B_i}{1 + i + s\frac{\bar{\gamma}_{EH}}{2}}\right] \quad (38)$$

In order to find the combined PDF, the inverse Laplace transform of $M_{\gamma_{tot}}(s)$ in (38) is taken

$$p_\gamma(\gamma) = J^{-1}\{M_{\gamma_{tot}}(s)\} \quad (39)$$

$$p_\gamma(\gamma) = N \sum_{i=0}^{N-1} (-1)^i \binom{N-1}{i} \left[A_i J^{-1}\{(1 + s\bar{\gamma}_{S,D})^{-1}\} + B_i J^{-1}\left\{\left(1 + i + s\frac{\bar{\gamma}_{EH}}{2}\right)^{-1}\right\}\right] \quad (40)$$

Using the fact that

$$J^{-1}\{(1 + As)^{-m}\} = \frac{1}{(m-1)!\,A^m} x^{m-1} exp\left(-\frac{x}{A}\right) \quad (41)$$

$$J^{-1}\{(1 + \bar{\gamma}_{S,D} s)^{-m}\} = \frac{1}{\bar{\gamma}_{S,D}} exp\left(-\frac{\gamma}{\bar{\gamma}_{S,D}}\right) \quad (42)$$

$$J^{-1}\left\{\left(1 + i + s\frac{\bar{\gamma}_{EH}}{2}\right)^{-1}\right\} = J^{-1}\left\{(1 + i)^{-1}\left(1 + s\frac{\bar{\gamma}}{2(1 + i)}\right)^{-1}\right\} \quad (43)$$

$$J^{-1}\left\{\left(1 + i + s\frac{\bar{\gamma}_{EH}}{2}\right)^{-1}\right\} = \frac{2}{\bar{\gamma}} exp\left(-\frac{2(1 + i)\gamma}{\bar{\gamma}}\right) \quad (44)$$

Substituting (42, 44) into (40), we finally obtain the combined PDF as in (29).

REFERENCES

[1] Z. Ding, I. Krikidis, B. Sharif, and H. Poor, "Wireless information and power transfer in cooperative networks with spatially random relays," *IEEE Trans. Wireless Commun.*, vol. 13, no. 8, pp. 4440–4453, Aug. 2014.

[2] J. Boyer, D. D. Falconer, and H. Yanikomeroglu, "Multihop diversity in wireless relaying channels," *IEEE Trans. Commun.*, vol. 52, no. 10, pp. 1820–1830, Oct. 2004.

[3] A. Andrawes and R. Nordin, "Survey on performance of adaptive modulation scheme with cooperative diversity in wireless systems," in *Proc. 1st International Conference on Telematics and Future Generation Networks (TAFGEN)*, 2015, pp. 65-70.

[4] X. Zhang, M. Hasna, and A. Ghrayeb, "An adaptive transmission scheme for two-way relaying with asymmetric data rates," *IEEE Transactions on Vehicular Technology*, vol. pp, no. 99, p. 1, 2015.

[5] S. Luo, R. Zhang, and T. J. Lim, "Optimal save-then-transmit protocol for energy harvesting wireless transmitters," *IEEE Trans. Wireless Commun.*, 2013.

[6] M. Alsharif, R. Nordin, and M. Ismail, "Survey of green radio communications networks: Techniques and recent advances," *Journal of Computer Networks and Communications*, vol. 2013, p. 13, 2013.

[7] M. Alsharif, R. Nordin, and M. Ismail, "Intelligent cooperation management of multi-radio access technology towards the green cellular networks for the twenty-twenty information society," *Telecommunication Systems*, vol. 65, no. 3, pp. 497-510, July 2017.

[8] J. H. Jawad, R. Nordin, and M. Ismail, "Opportunities and challenges for near-field wireless power transfer: A Review," *Energies*, vol. 10, no. 7, p. 1022, Jul. 2017.

[9] R. Zhang and C. K. Ho, "MIMO broadcasting for simultaneous wireless information and power transfer," *IEEE Trans. Wireless Commun.*, vol. 12, no. 5, pp. 1989-2001, May 2013.

[10] Y. Liu, "Wireless Information and power transfer for multi-relay assisted cooperative communication," *IEEE Comm. Letters*, vol. 20, no. 4, pp. 784–787, Apr. 2016.

[11] L. Liu, R. Zhang, and K. C. Chua, "Wireless information and power transfer: A dynamic power splitting approach," *IEEE Trans. Commun.*, vol. 61, no. 9, pp. 3990– 4001, Sep. 2013.

[12] S. Gong, L. Duan, and N. Gautam, "Optimal scheduling and beam-forming in relay networks with energy harvesting constraints," *IEEE Trans. Wireless Commun.*, 2015.

[13] Y. Gu and S. Aïssa, "RF-Based energy harvesting in decode-and-forward relaying systems: Ergodic and outage capacities," *IEEE Trans. On Wireless Commun.*, vol. 14, no. 11, pp. 6425- 6434, Nov. 2015.

[14] M. K. Chang and F. T. Chein, "Adaptive modulation in decode and forward cooperative communications with limited source relay CSI," *IEEE Commun. Letters*, vol. 18, no. 12, pp. 2157-2160, Dec., 2014.

[15] S. S. Soliman and N. C. Beaulieu, "Exact analysis of dual-hop AF maximum End-to-End SNR relay selection," *IEEE Tans. on Comm.* vol. 60, no. 8, pp. 2135-2144, Aug. 2012.

[16] A. Annamalai, B. Modi, and R. Palat, "Analysis of amplify-and-forward cooperative relaying with adaptive

modulation in nakagami-m fading channels," in *Proc. 8th Annual IEEE Consumer Communications and Networking Conference* - Work *in Progress (Short Papers)*, 2011, pp. 1116-117.
[17] S. S. Soliman and N. C. Beaulieu," Dual-Hop AF Systems with Maximum End-to-End SNR Relay Selection Over Nakagami-*m* and Rician Fading Links," in *Proc. International Conference on Computing, Networking and Communications (ICNC) Workshop on Computing, Networking and Communications*, 2013, pp. 155-161.
[18] B. Lee and C. Lee, "Performance analysis of incremental hop selection scheme with adaptive modulation for cooperative multi-hop networks," *IEEE Trans. on Wireless Commun.*, vol. 14, no. 1, pp. 435-445, Jan. 2015.
[19] Y. Gu and S. Aïssa, "RF-Based energy harvesting in decode-and-forward relaying systems: Ergodic and outage capacities," *IEEE Transactions on Wireless Communications*, vol. 14, no. 11, pp. 6425-6434, Nov. 2015.
[20] A. Andrawes, R. Nordin, and M. Ismail, "Energy harvesting with cooperative networks and adaptive transmission," in *Proc. IEEE Jordan Conference on Applied Electrical Engineering and Computing Technologies (AEECT)*, Aqaba, Jordan, 2017.
[21] S. Sesia, I Toufik, and M Baker, *LTE – The UMTS Long Term Evolution from Theory to Practice*, 2nd edition, New York: John Wiley & Sons, 2011.
[22] A. Andrawes, "Performance of adaptive modulation with generalized selection combining in different practical scenarios," in *Proc. Seventh International Conference on Computer Engineering & Systems (ICCES)*, 2013, pp. 233-237.
[23] A. Ribeiro, X. Cai, and G. B. Giannakis, "Symbol error probabilities for general cooperative links," *IEEE Trans. Wireless Commun.*, vol. 4, no. 3, 2005.
[24] Hasna and Alouini, "Harmonic mean and end-to-end performance of transmission systems with relays," *IEEE Trans. Commun.*, vol. 52, no. 1, 2004.
[25] M. K. Simon and M. S. Alouini, *Digital Communication over Fading Channels*, John Wiley and Sons, New York, NY, USA, 2000.

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