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AF Relaying with Energy Harvesting Source and Relay

Yunfei Chen, Rui Shi, Wei Feng, Ning Ge

***Abstract*— In the conventional energy harvesting amplify-and-forward relaying, only the relay harvests energy from the source. In this work, a new energy harvesting relaying protocol is proposed, where the source also harvests energy from the relay, in addition to the energy harvesting relay. The performances of the new protocols using two different strategies are analyzed. Numerical results show that the new protocols have certain gain over the conventional protocol.**

***Index Terms*— Amplify-and-forward, energy harvesting, power-splitting, relaying, time-switching.**

I. INTRODUCTION

As a promising solution to encouraging relaying, energy harvesting can be used as an application of simultaneous information and energy transfer [1]. Two harvesting methods, time-switching (TS) and power-splitting (PS), were proposed in [2]. Consequently, relaying with energy harvesting has been studied in the literature [3] - [9].

Specifically, in the seminal paper [3], energy harvesting was applied to amplify-and-forward (AF) relaying. In [4], the total energy harvested from multiple sources was optimally allocated among different destinations. In [5], the effect of large-scale network interference on energy harvesting decode-and-forward (DF) was considered. Reference [6] studied the effect of the random location of the relay on DF relaying. Furthermore, reference [7] maximized the achievable throughput of an AF energy harvesting system. A similar problem was studied in [8] for DF. In [9], the achievable throughput of an AF energy harvesting system was optimized. In all these works, the conventional energy harvesting relaying protocol was assumed, where in the broadcasting phase, the source transmits signal to the relay for energy harvesting. This can be further improved by allowing the source to harvest energy from the relay during the relaying phase to maximize the energy use.

In this work, a new energy harvesting AF relaying protocol is proposed where the relay harvests energy in the broadcasting phase and the source harvests energy in the relaying phase. The harvested energy at the source is either used immediately in the next transmission or accumulated to conduct more transmissions. The performances of these two strategies are analyzed and compared with the conventional protocol. Numerical results show that the new protocols can achieve certain throughput gain due to the extra energy harvested at the source.

II. SYSTEM MODEL

Consider an AF relaying system with three nodes: the source, the relay and the destination. Each has a single antenna and works in a half-duplex mode. There is no direct link between the source and the destination. This could be the case when the destination moves out of the transmission range of the source or when there is obstacle between the source and the destination [10], [11]. This model is similar to that in [3]. Assume that there are E_t joules of total energy initially available at the source and that the total time of transmission is T seconds.

A. TS

Assume that the TS coefficient is α. The relay harvests energy from the source for αT seconds and then receives information from the source for $\frac{1-\alpha}{2}T$ seconds in the broadcasting phase. The received signal at the relay can be given by

$$y_r[k] = \sqrt{P_s}\frac{h}{\sqrt{L_{sr}}}s[k] + n_{ra}[k] + n_{rc}[k] \tag{1}$$

where P_s is the initial transmission power of the source, h is the fixed channel gain of the source-to-relay link, L_{sr} is the path loss in this link, $s[k] = \pm 1$ is the transmitted information symbol, $n_{ra}[k]$ is the additive white Gaussian noise (AWGN) incurred at the RF front as a Gaussian random variable with mean zero and variance σ_{ra}^2, and $n_{rc}[k]$ is the AWGN incurred in the RF-to-baseband conversion as a Gaussian random variable with mean zero and variance σ_{rc}^2. Thus, the harvested energy at the relay is derived as $E_{hr} = \eta P_s \frac{|h|^2}{L_{sr}}\alpha T$, where η is the constant conversion efficiency of the energy harvester, as assumed in most previous works [3] - [9]. In the relaying phase, the relay transmits the signal to the destination for $\frac{1-\alpha}{2}T$ seconds such that the received signal at the destination is

$$y_d[k] = \frac{g}{\sqrt{L_{rd}}}\sqrt{P_r}b_t y_r[k] + n_{da}[k] + n_{dc}[k] \tag{2}$$

where g is the fixed channel gain of the relay-to-destination link, L_{rd} is the path loss between relay and destination, $P_r = \frac{E_{hr}}{\frac{1-\alpha}{2}T} = \frac{2\alpha\eta}{1-\alpha}P_s\frac{|h|^2}{L_{sr}}$ is the transmission power of the relay, $b_t y_r[k]$ is the normalized transmitted signal, normalized with respect to the average power of $y_r[k]$ as $b_t = \frac{1}{\sqrt{P_s\frac{|h|^2}{L_{sr}} + \sigma_{ra}^2 + \sigma_{rc}^2}}$, $n_{da}[k]$ is the RF front noise with mean zero and variance σ_{da}^2, and $n_{dc}[k]$ is the conversion noise with mean zero and variance σ_{dc}^2. In this work, assume that the circuit power at the relay node is negligible, similar to the assumption used in [3]- [9].

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Unlike the conventional relaying protocol, in the new protocol, the source also harvests energy from the relay in the relaying phase such that the received signal at the source is

$$y_s[k] = \frac{h}{\sqrt{L_{sr}}}\sqrt{P_r} b_t y_r[k] + n_{sa}[k] \tag{3}$$

where h and L_{sr} are used due to channel reciprocity and $n_{sa}[k]$ is the AWGN at the source. Using (1) and (3), the harvested energy at the source can be derived as

$$E_{hs} = \eta^2 \alpha \frac{P_s^2(|h|^2/L_{sr})^3 T}{P_s|h|^2/L_{sr} + \sigma_{ra}^2 + \sigma_{rc}^2}. \tag{4}$$

Note that, although the energy received at the source is attenuated twice, it may not be negligibly small, as the relay has to amplify the signal before relaying for reliable decoding at the destination. Thus, there is amplification between the two attenuations. From (2) and (3), the signal transmitted by the relay is received with a power of $\frac{P_r|h|^2}{L_{sr}}$ for energy harvesting at the source and a power of $\frac{P_r|g|^2}{L_{rd}}$ for decoding at the destination, as $b_t y_r[k]$ has a normalized power of 1. Thus, for identically distributed links, the received energy at the source is comparable to that at the destination. Since the received energy at the destination is often strong required for reliable decoding, the received energy at the source will be considerable too. Although the source receives considerable energy, the final converted energy is subject to a further loss, described by the conversion efficiency η in (4) with $0 < \eta < 1$. Also, the sensitivity of the information decoder at the destination may be much higher than that of the energy harvester at the source. However, existing harvesters already have sensitivity as low as -22.6 dBm (5.5 μW) in 2008 [12], while studies show that the ambient RF energy is often on the order of milli-Watt or micro-Watt [13], high enough to be picked up by the sensitive energy harvesters.

B. PS

Assume that ρ is the PS factor. In this case, the source transmits the signal to the relay for $\frac{T}{2}$ seconds, and part of this signal is received at the relay for information delivery as

$$y_r[k] = \sqrt{(1-\rho)P_s}\frac{h}{\sqrt{L_{sr}}} s[k] + \sqrt{1-\rho} n_{ra}[k] + n_{rc}[k] \tag{5}$$

and part of this signal is harvested by the relay as $E_{hr} = \eta\rho P_s \frac{|h|^2}{L_{sr}} \frac{T}{2}$. In the relaying phase, the received signal at the destination is

$$y_d[k] = \frac{g}{\sqrt{L_{rd}}}\sqrt{P_r} b_p y_r[k] + n_{da}[k] + n_{dc}[k] \tag{6}$$

where $P_r = \frac{E_{hr}}{T/2} = \eta\rho P_s \frac{|h|^2}{L_{sr}}$ in this case and $b_p = \frac{1}{\sqrt{(1-\rho)P_s\frac{|h|^2}{L_{sr}} + (1-\rho)\sigma_{ra}^2 + \sigma_{rc}^2}}$.

Also, unlike the conventional relaying protocol, in the relaying phase of the new protocol, the source harvests energy from the relay transmission with a received signal of

$$y_s[k] = \frac{h}{\sqrt{L_{sr}}}\sqrt{P_r} b_p y_r[k] + n_{sa}[k] \tag{7}$$

and the harvested energy is

$$E_{hs} = \frac{\eta^2\rho(1-\rho)P_s^2(|h|^2/L_{sr})^3 T/2}{(1-\rho)P_s|h|^2/L_{sr} + (1-\rho)\sigma_{ra}^2 + \sigma_{rc}^2} \tag{8}$$

which will not be negligibly small and is comparable to the received energy at the destination.

III. ACHIEVABLE THROUGHPUT AND OUTAGE PROBABILITY

A. TS

For the conventional relaying protocol using TS, the source node transmits the signal for a duration of $\alpha T + \frac{1-\alpha}{2}T$ with a transmission power of P_s, where the first part is the energy transfer time and the second part is the information delivery time from the source to the relay. Thus, each transmission costs the source an energy of $E_i = \left[\alpha T + \frac{1-\alpha}{2}T\right] P_s$ and the total number of transmissions the source can make in the conventional protocol using TS is $K_{TS}^{Con} = \frac{E_t}{E_i} = \left\lfloor \frac{E_t}{P_s T}\frac{2}{1+\alpha}\right\rfloor$, where $\lfloor\cdot\rfloor$ is the floor function. For TS, the end-to-end signal-to-noise ratio (SNR) is

$$\gamma_{TS} = \frac{P_s\gamma_d\gamma_r}{\gamma_d + \frac{1-\alpha}{2\alpha\eta}\frac{1+1/(P_s\gamma_r)}{\sigma_{ra}^2+\sigma_{rc}^2}} \tag{9}$$

where $\gamma_d = \frac{|g|^2}{L_{rd}(\sigma_{da}^2+\sigma_{dc}^2)}$ and $\gamma_r = \frac{|h|^2}{L_{sr}(\sigma_{ra}^2+\sigma_{rc}^2)}$. Thus, the overall achievable throughput in all transmissions using an initial energy of E_t at the source node is derived as

$$C_{TS}^{Con} = \frac{1-\alpha}{2} K_{TS}^{Con} \cdot \log_2(1+\gamma_{TS}) \tag{10}$$

which is only achievable when the input is a continuous circularly symmetric complex Gaussian signal but nevertheless is also a good performance indicator for finite inputs like binary phase shift keying as assumed here and in [3] - [9].

For the new protocol, two strategies are considered. In the first strategy, all the harvested energies at the source node will be accumulated until the K_{TS}^{Cov} transmissions are finished. Then, they will be used to conduct more transmissions. The new total number of transmissions is

$$K_{TS}^{New} = \left\lfloor K_{TS}^{Con}\left(1 + \frac{2\eta^2\alpha}{1+\alpha}\cdot\frac{P_s\gamma_r^3(\sigma_{ra}^2+\sigma_{rc}^2)^2}{P_s\gamma_r+1}\right)\right\rfloor. \tag{11}$$

Since the achievable throughput for each transmission remains the same as that in the conventional relaying protocol, one has the total achievable throughput in the first strategy as

$$C_{TS}^{New1} = \frac{1-\alpha}{2} K_{TS}^{New} \cdot \log_2(1+\gamma_{TS}). \tag{12}$$

For Rayleigh fading channels, γ_d and γ_r in γ_{TS} are exponential random variables with probability density functions (PDFs) of $f(\gamma_d) = \frac{1}{\bar{\gamma_d}}e^{-\frac{\gamma_d}{\bar{\gamma_d}}}$ and $f(\gamma_r) = \frac{1}{\bar{\gamma_r}}e^{-\frac{\gamma_r}{\bar{\gamma_r}}}$, respectively, where $\bar{\gamma_d} = \frac{E\{|g|^2\}}{L_{rd}(\sigma_{da}^2+\sigma_{dc}^2)}$ and $\bar{\gamma_r} = \frac{E\{|h|^2\}}{L_{sr}(\sigma_{ra}^2+\sigma_{rc}^2)}$. Thus, the average achievable throughput is

$$\begin{aligned}\bar{C}_{TS}^{New1} \quad = \quad & \int_0^\infty\int_0^\infty \frac{1-\alpha}{2\bar{\gamma_d}\bar{\gamma_r}} K_{TS}^{New} \cdot \log_2(1+\gamma_{TS}) \\ & e^{-\frac{\gamma_d}{\bar{\gamma_d}} - \frac{\gamma_r}{\bar{\gamma_r}}} d\gamma_r d\gamma_d \end{aligned} \tag{13}$$

by using (12), $f(\gamma_d)$ and $f(\gamma_r)$. The next step is to solve the integration in (13). From (9), one has $1+\gamma_{TS} = \frac{P_s\gamma_d\gamma_r+\gamma_d+\frac{1-\alpha}{2\alpha\eta}\frac{1+1/(P_s\gamma_r)}{\sigma_{ra}^2+\sigma_{rc}^2}}{\gamma_d+\frac{1-\alpha}{2\alpha\eta}\frac{1+1/(P_s\gamma_r)}{\sigma_{ra}^2+\sigma_{rc}^2}}$. Thus, $\log_2(1+\gamma_{TS}) = \log_2(P_s\gamma_d\gamma_r+\gamma_d+\frac{1-\alpha}{2\alpha\eta}\frac{1+1/(P_s\gamma_r)}{\sigma_{ra}^2+\sigma_{rc}^2}) - \log_2(\gamma_d+\frac{1-\alpha}{2\alpha\eta}\frac{1+1/(P_s\gamma_r)}{\sigma_{ra}^2+\sigma_{rc}^2})$. Using this relationship in (13), $\log_2(1+\gamma_{TS})$ will be splitted into two terms and using [14, eq. (4.337.1)] for each term, one can solve the integration over γ_d as

$$\bar{C}_{TS}^{New1} = \frac{1-\alpha}{2\bar{\gamma}_r\ln 2}\int_0^\infty K_{TS}^{New}e^{-\frac{\gamma_r}{\bar{\gamma}_r}} \tag{14}$$
$$[e^{\beta\frac{P_s\gamma_r+1}{P_s\gamma_r}}Ei(-\beta\frac{P_s\gamma_r+1}{P_s\gamma_r}) - e^{\frac{\beta}{P_s\gamma_r}}Ei(-\frac{\beta}{P_s\gamma_r})]d\gamma_r$$

where $\beta = \frac{1-\alpha}{2\alpha\eta\bar{\gamma}_d(\sigma_{ra}^2+\sigma_{rc}^2)}$ and $Ei(\cdot)$ is the exponential integral function [14, eq. (8.211.1)]. Note that K_{TS}^{New} cannot be moved out of the integral, as it is a function of γ_r from (11).

Also, the outage probability is defined as $P_{out}(x) = Pr\{\gamma_{TS} < x\}$. Using (9), it becomes

$$P_{out}(x) = Pr\{(P_s\gamma_r - x)\gamma_d < x\frac{1-\alpha}{2\alpha\eta}\frac{1+1/(P_s\gamma_r)}{\sigma_{ra}^2+\sigma_{rc}^2}\} \tag{15}$$

by multiplying both sides of the inequality with the denominator of γ_{TS}. This further gives

$$P_{out}(x) = Pr\{P_s\gamma_r < x\} \tag{16}$$
$$+Pr\{P_s\gamma_r > x, \gamma_d < \frac{x}{P_s\gamma_r - x}\frac{1-\alpha}{2\alpha\eta}\frac{1+1/(P_s\gamma_r)}{\sigma_{ra}^2+\sigma_{rc}^2}\}$$

where the first term is for $P_s\gamma_r < x$ and the second term is for $P_s\gamma_r > x$. Thus,

$$P_{out}(x) = \int_0^{x/P_s} f(\gamma_r)d\gamma_r \tag{17}$$
$$+\int_{x/P_s}^\infty \int_0^{\frac{x}{P_s\gamma_r-x}\frac{1-\alpha}{2\alpha\eta}\frac{1+1/(P_s\gamma_r)}{\sigma_{ra}^2+\sigma_{rc}^2}} f(\gamma_d)f(\gamma_r)d\gamma_d d\gamma_r$$

Then, by using $f(\gamma_d)$ and $f(\gamma_r)$ in (17), solving the inner integral of the second term in (17) and letting $t = P_s\gamma_r - x$, the outage probability is derived as

$$P_{out}(x) = 1 - \frac{1}{P_s\bar{\gamma}_r}\int_0^\infty e^{-\frac{1-\alpha}{2\alpha\eta\bar{\gamma}_d(\sigma_{ra}^2+\sigma_{rc}^2)}\frac{x}{t}(1+\frac{1}{t+x})-\frac{t+x}{P_s\bar{\gamma}_r}}dt. \tag{18}$$

This outage applies to both the conventional protocol and the new protocol using the first strategy. Note that in the asymptotic case when $\bar{\gamma}_d \to \infty$, the first term in the exponent of (18) can be ignored such that $P_{out}(x) \to 1 - e^{-\frac{x}{P_s\bar{\gamma}_r}}$. This means that, when the relay-to-destination link has good quality, the outage is mainly determined by $\bar{\gamma}_r$ and it improves when the source-to-relay link becomes better. Also, when $x \to \infty$, $1+\frac{1}{t+x} \to 1$ in the exponent of (18) such that $P_{out}(x) \to 1 - e^{-\frac{x}{P_s\bar{\gamma}_r}}\sqrt{\frac{2(1-\alpha)x}{2\alpha\eta\bar{\gamma}_d(\sigma_{ra}^2+\sigma_{rc}^2)P_s\bar{\gamma}_r}}K_1\left(\sqrt{\frac{2(1-\alpha)x}{2\alpha\eta\bar{\gamma}_d(\sigma_{ra}^2+\sigma_{rc}^2)P_s\bar{\gamma}_r}}\right)$ by using [14, eq. 3.471.9]. Furthermore, $K_1(u) \approx \frac{1}{u}$ when u is large, which gives $P_{out}(x) \approx 1 - e^{-\frac{x}{P_s\bar{\gamma}_r}}$ when $\sqrt{\frac{2(1-\alpha)x}{2\alpha\eta\bar{\gamma}_d(\sigma_{ra}^2+\sigma_{rc}^2)P_s\bar{\gamma}_r}}$ is large. This means that, when $x \to \infty$ such that the receiver sensitivity is very low in a practical system, the outage is mainly determined by the transmission power P_s and the source-to-relay link $\bar{\gamma}_r$, and it improves when the source-to-relay link becomes better. When $x = 0$, $P_{out}(x) = 0$, indicating that the outage will be very small when the receiver has high sensitivity in practice.

In the second strategy, the harvested energy will be used immediately in the next relay transmission to increase the source transmission power. In particular, one has

$$E_{hs}^{(i+1)} = \eta^2\alpha\frac{(P_s^{(i)})^2\gamma_r^3T(\sigma_{ra}^2+\sigma_{rc}^2)^2}{P_s^{(i)}\gamma_r+1}$$
$$P_s^{(i+1)} = P_s + \frac{E_{hs}^{(i+1)}}{T}\frac{2}{1+\alpha}$$
$$\gamma_{TS}^{(i+1)} = \frac{P_s^{(i+1)}\gamma_d\gamma_r}{\gamma_d+\frac{1-\alpha}{2\alpha\eta}\frac{1+1/(P_s^{(i+1)}\gamma_r)}{\sigma_{ra}^2+\sigma_{rc}^2}}. \tag{19}$$

where $i = 1, 2, \cdots, K_{TS}^{Con}$, $E_{hs}^1 = 0$ and $P_s^1 = P_s$. In this case, the total achievable throughput is derived as

$$C_{TS}^{New2} = \frac{1-\alpha}{2}\sum_{i=1}^{K_{TS}^{Con}}\log_2(1+\gamma_{TS}^{(i)}). \tag{20}$$

Using a similar method to before, the average achievable throughput in Rayleigh fading channels can be derived as

$$\bar{C}_{TS}^{New2} = \frac{1-\alpha}{2\bar{\gamma}_r\ln 2}\sum_{i=1}^{K_{TS}^{Con}}\int_0^\infty e^{-\frac{\gamma_r}{\bar{\gamma}_r}}[e^{\beta\frac{P_s^{(i)}\gamma_r+1}{P_s^{(i)}\gamma_r}} \tag{21}$$
$$Ei(-\beta\frac{P_s^{(i)}\gamma_r+1}{P_s^{(i)}\gamma_r}) - e^{\frac{\beta}{P_s^{(i)}\gamma_r}}Ei(-\frac{\beta}{P_s^{(i)}\gamma_r})]d\gamma_r$$

where $P_s^{(i)} = P_s + \frac{2\eta^2\alpha}{1+\alpha}\frac{(P_s^{(i-1)})^2\gamma_r^3(\sigma_{ra}^2+\sigma_{rc}^2)^2}{P_s^{(i-1)}\gamma_r+1}$ from (19) and is a function of γ_r. Also, the outage probability can be shown as

$$P_{out}(x) = 1-\frac{1}{\bar{\gamma}_r}\int_\theta e^{-\frac{1-\alpha}{2\alpha\eta\bar{\gamma}_d(\sigma_{ra}^2+\sigma_{rc}^2)}\frac{x}{P_s^{(i)}\gamma_r-x}(1+\frac{1}{P_s^{(i)}\gamma_r})-\frac{\gamma_r}{\bar{\gamma}_r}}d\gamma_r. \tag{22}$$

where θ is $P_s^{(i)}\gamma_r > x$.

B. PS

The calculation in the case of PS is similar. In the conventional protocol, each relay transmission costs the source an energy of $E_i = \frac{T}{2}P_s$ and the total number of transmissions is then $K_{PS}^{Con} = \left\lfloor\frac{2E_t}{P_sT}\right\rfloor$. Also, using PS, the end-to-end SNR is

$$\gamma_{PS} = \frac{P_s\gamma_d\gamma_p}{\gamma_d+\frac{1-\rho}{\eta\rho}\frac{1+1/(P_s\gamma_p)}{(1-\rho)\sigma_{ra}^2+\sigma_{rc}^2}} \tag{23}$$

where $\gamma_p = \frac{|h|^2}{L_{sr}[\sigma_{ra}^2+\sigma_{rc}^2/(1-\rho)]}$ and other symbols are defined as before. This gives the total achievable throughput of the conventional protocol using PS as

$$C_{PS}^{Con} = \frac{K_{PS}^{Con}}{2}\log_2(1+\gamma_{PS}). \tag{24}$$

In the new protocol, using the first strategy, the number of total transmissions is calculated as

$$K_{PS}^{New} = \left\lfloor K_{PS}^{Con}\left(1+\frac{\frac{\eta^2\rho}{(1-\rho)^2}P_s\gamma_p^3[(1-\rho)\sigma_{ra}^2+\sigma_{rc}^2]^2}{P_s\gamma_p+1}\right)\right\rfloor. \tag{25}$$

Thus, the total achievable throughput is

$$C_{PS}^{New1} = \frac{K_{PS}^{New}}{2} \log_2(1 + \gamma_{PS}). \tag{26}$$

In Rayleigh fading channels, γ_p is an exponential random variable with PDF $f(\gamma_p) = \frac{1}{\bar{\gamma}_p} e^{-\frac{\gamma_p}{\bar{\gamma}_p}}$, where $\bar{\gamma}_p = \frac{E\{|h|^2\}}{L_{sr}[\sigma_{ra}^2+\sigma_{rc}^2/(1-\rho)]}$. Similarly, the average achievable throughput can be derived as

$$\begin{aligned} \bar{C}_{PS}^{New1} &= \frac{1}{2\bar{\gamma}_p \ln 2} \int_0^\infty K_{PS}^{New} e^{-\frac{\gamma_p}{\bar{\gamma}_p}} [e^{\mu \frac{P_s \gamma_p + 1}{P_s \gamma_p}} \\ &\quad Ei(-\mu \frac{P_s \gamma_p + 1}{P_s \gamma_p}) - e^{\frac{\mu}{P_s \gamma_p}} Ei(-\frac{\mu}{P_s \gamma_p})] d\gamma_p \end{aligned} \tag{27}$$

where $\mu = \frac{1-\rho}{\eta\rho\bar{\gamma}_d[(1-\rho)\sigma_{ra}^2+\sigma_{rc}^2]}$. The outage probability can be obtained by replacing $\bar{\gamma}_r$ with $\bar{\gamma}_p$ and $\frac{1-\alpha}{2\alpha\eta(\sigma_{ra}^2+\sigma_{rc}^2)}$ with $\frac{1-\rho}{\eta\rho[(1-\rho)\sigma_{ra}^2+\sigma_{rc}^2]}$ in (18).

Using the second strategy for the new protocol, one has

$$\begin{aligned} E_{hs}^{(i+1)} &= \frac{\frac{\eta^2 \rho}{(1-\rho)^2} (P_s^{(i)})^2 \gamma_p^3 [(1-\rho)\sigma_{ra}^2 + \sigma_{rc}^2]^2 T/2}{P_s^{(i)} \gamma_p + 1} \\ P_s^{(i+1)} &= P_s + \frac{2E_{hs}^{(i+1)}}{T} \\ \gamma_{PS}^{i+1} &= \frac{P_s^{(i+1)} \gamma_d \gamma_p}{\gamma_d + \frac{1-\rho}{\eta\rho} \frac{1+1/(P_s^{(i+1)}\gamma_p)}{(1-\rho)\sigma_{ra}^2+\sigma_{rc}^2}}. \end{aligned} \tag{28}$$

The total achievable throughput is

$$C_{PS}^{New2} = \frac{1}{2} \sum_{i=1}^{K_{PS}^{Con}} \log_2(1 + \gamma_{PS}^{(i)}). \tag{29}$$

The average achievable throughput in Rayleigh fading channels can be derived as

$$\begin{aligned} \bar{C}_{PS}^{New2} &= \frac{1}{2\bar{\gamma}_p \ln 2} \sum_{i=1}^{K_{PS}^{Con}} \int_0^\infty e^{-\frac{\gamma_p}{\bar{\gamma}_p}} [e^{\mu \frac{P_s^{(i)} \gamma_p + 1}{P_s^{(i)} \gamma_p}} \\ &\quad Ei(-\mu \frac{P_s^{(i)} \gamma_p + 1}{P_s^{(i)} \gamma_p}) - e^{\frac{\mu}{P_s^{(i)} \gamma_p}} Ei(-\frac{\mu}{P_s^{(i)} \gamma_p})] d\gamma_p \end{aligned} \tag{30}$$

where $P_s^{(i)} = P_s + \frac{\frac{\eta^2\rho}{(1-\rho)^2}(P_s^{(i-1)})^2\gamma_p^3[(1-\rho)\sigma_{ra}^2+\sigma_{rc}^2]^2 T/2}{P_s^{(i-1)}\gamma_p+1}$ from (28). The outage probability is obtained by replacing γ_r with γ_p, $\bar{\gamma}_r$ with $\bar{\gamma}_p$, and $\frac{1-\alpha}{2\alpha\eta(\sigma_{ra}^2+\sigma_{rc}^2)}$ with $\frac{1-\rho}{\eta\rho[(1-\rho)\sigma_{ra}^2+\sigma_{rc}^2]}$ in (22). The above protocol requires that the source can also operate in the receiving mode in order to harvest energy from the relay. Such applications have been widely used in the previous works.

IV. Numerical Results and Discussion

In this section, numerical examples are presented to show the gain of the new protocol. In Figs. 1 and 2, the values of α and ρ are calculated by numerically searching for the best values that maximize $\frac{1-\alpha}{2}\log_2(1+\gamma_{TS})$ and $\frac{1}{2}\log_2(1+\gamma_{PS})$, respectively, for the conventional protocols for two reasons. First, the values of α and ρ need to be the same in both conventional and new protocols for a fair comparison. Second, the optimal values of α and ρ for the conventional protocols are easier to obtain. For fixed h, the value of $\frac{h^2}{L_{sr}}$ is determined by L_{sr}. A singular model for path loss is $L_{sr} = d_{sr}^m$, where d_{sr} is the distance and m is the path loss exponent [5]. This model requires $d_{sr} \geq 1$ to avoid issues for distances less than 1 meter. A non-singular model is $L_{sr} = d_{sr}^m + 1$ [15]. This model gives a meaningful channel gain at $d_{sr} = 1$ without any normalization. We will use the non-singular model. In the following, we examine the effects of η and d_{sr} on the performance gain. Other parameters are set as $P_s = 1\ Watt$, $E_t = 100\ Joules$, $T = 1\ second$, $\sigma_{ra}^2 = \sigma_{rc}^2 = \sigma_{da}^2 = \sigma_{dc}^2 = \sigma^2 = 0.01$, $m = 2$, and $h = g = 1$, similar to [3]. The choices of distances are for illustration purpose only and are similar to [3]. The gain is calculated as the difference between the achievable throughputs of the new protocol and the conventional protocol divided by that of the conventional protocol. The star marker represents simulation results.

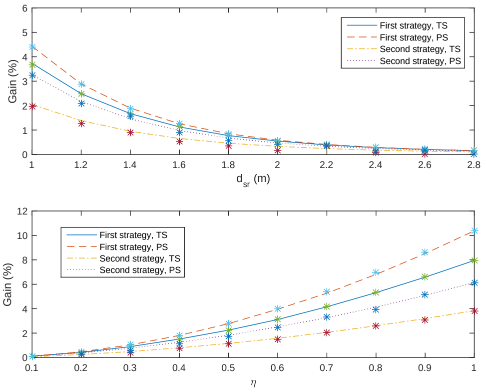

Fig. 1. Gain vs. d_{sr} when $d_{rd} = 3 - d_{sr}$, $\eta = 0.5$ and gain vs. η when $d_{sr} = 1.2m$ and $d_{rd} = 1.2m$ in AWGN channels.

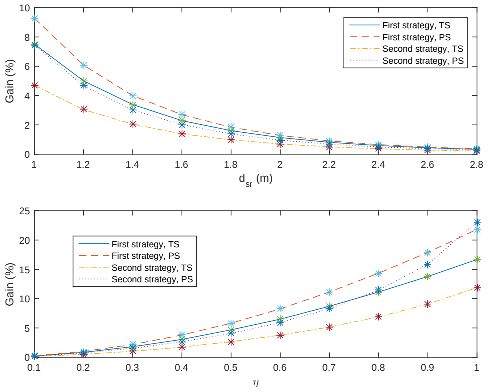

Fig. 2. Gain vs. d_{sr} when $d_{rd} = 3 - d_{sr}$, $\eta = 0.5$ and gain vs. η when $d_{sr} = 1.2m$, $d_{rd} = 1.2m$ in Rayleigh fading.

Fig. 1 shows the results in AWGN channels. Since the gain is always positive, the new protocol outperforms the conventional protocol in all the cases, as expected. Also, the first strategy has a larger gain than the second strategy in most cases, while PS has a larger gain than TS, as PS normally has a larger achievable throughput than TS by not having a dedicated harvesting time. As well, the gain increases when η increases or when d_{sr} decreases. Fig. 2 shows the Rayleigh fading

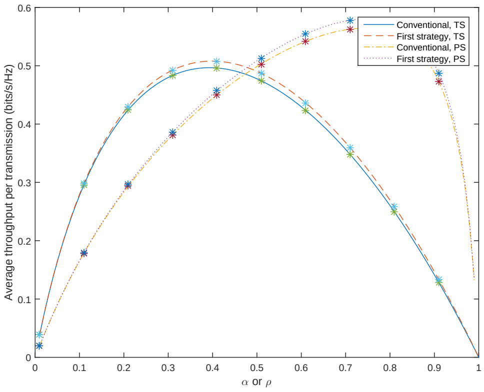

Fig. 3. Achievable throughput per transmission vs. α or ρ when $d_{sr} = d_{rd} = 1.2m$ and $\eta = 0.5$ in AWGN channels.

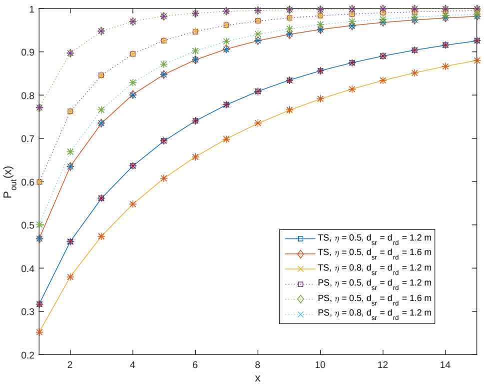

Fig. 4. Outage probability of the first strategy when $\alpha = \rho = 0.5$ in Rayleigh fading channels.

channels when $E\{|h|^2\} = E\{|g|^2\} = 1$. Similar observations can be made. These findings suggest that it is beneficial to have extra harvesting at the source. To maximize this benefit, it is advisable to use the first strategy that accumulates energy for more transmissions and to use PS that has larger achievable throughput. Also, it is important to design energy harvesters with high conversion efficiency and to place the nodes in relevant positions in order to have a reasonable gain.

Fig. 3 shows the achievable throughput per transmissions vs. α for TS or ρ for PS. One sees that optimum values of α and ρ exist. This finding suggests that it is important to choose the parameters of α and ρ whenever possible. Fig. 4 shows the outage probability of the first strategy in Rayleigh fading. It decreases when d_{sr} or d_{rd} decrease or when η increases. This finding suggests that, to keep the outage rate within a tolerable level, one must have either a highly efficient energy harvester or carefully choose the locations of the nodes.

In the case of multiple sources, one may use dynamic channel assignment [17] or channel allocation [18] in the first hop to increase energy efficiency further, which could be a future research topic. Also, reference [19] proposed a self-energy recycling scheme by using an additional antenna at the relay to harvest the signal transmitted by the relay. This allows more efficient harvesting, as the signal suffers from less path loss. However, this scheme replenishes the energy at the relay, not at the source which has data for transmission. An interesting future work is to combine them at both the relay and the source for improved energy efficiency.

V. CONCLUSION

In this paper, a new energy harvesting relaying protocol has been proposed. Numerical results have show certain performance gain of the new protocol. This work assumes fixed locations of the nodes. An interesting work for future investigation is to consider the random locations of the nodes.

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