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Optimal Energy Harvesting Strategy in Relaying Networks: Dynamic Allocation Scheme and Performance Analysis

Dinh-Thuan Do[1]

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Abstract
This paper evaluates the performance of a wireless powered communications system, where an energy-aware relay can ability of controlling proper energy harvesting parameters for obtaining maximal throughput. Considering a power splitting approach, the relay first can calculate percentage of harvested wireless energy from power supply source, and then transmits information to the destination. This paper proposes the dynamic harvesting power allocation policy for energy harvesting and analytical expressions for the delay-limited and delay-tolerant throughput related to amplify-and-forward relaying mode. In particular, the optimal power coefficients can be derived in closed-form expressions, in which the maximal throughput can be obtained in special case, i.e., high transmit power regime. In addition, the impact of transmit power, power splitting fraction, the fixed rate factors, noise levels are well studied. Simulation results validate the theoretical expressions and show the effectiveness of the proposed policy.

Keywords Dynamic harvesting power allocation · Energy harvesting · Amplify and forward

1 Introduction

Recently, information and energy transmission via wireless energy harvesting (EH) have drawn noteworthy considerations as a consequence of interesting capability to lengthen the operation period of wireless systems, particularly in energy-aware relay nodes which can be recommended in heterogeneous network with many tiers [1–8]. In such networks, the users located in border areas will remain their operations in acceptable quality thanks to energy harvesting technique. With advantage of modern circuit designs, the information can be able interpreted and collect energy concurrently from the received signal carried by the radio frequency (RF) signal. In previous work, two applied receiver designs including time switching (TS) and power splitting (PS) that have been widely implemented [1]. Having a look on the fundamental power-splitting design in the receiver circuit still remain and

✉ Dinh-Thuan Do
dodinhthuan@tdtu.edu.vn

[1] Wireless Communications Research Group, Faculty of Electrical and Electronics Engineering, Ton Duc Thang University, Ho Chi Minh City, Vietnam

guarantee normal operation of the conventional communication systems and here is prominent candidate for future wireless standards.

In [2], an ambitious switching policy was taken into account, in which the wireless powered receiver can selects data communicating and energy communicating which adapts to processing procedure at the relay node make sure that decoding at the destination is successful.. The authors in [3] considered multiple source–destination pairs and a EH relay in terms of cooperative network. Since a large-scale approach of RF transmission was implemented in EH technology, a network performance with random quantity of transmitter–receiver pairs was investigated effectively with the powerful mathematics tools such as stochastic geometry. In addition, a harvest-then-cooperate (HTC) protocol relying on the TS architecture for an amplify-and-forward (AF) relaying network was considered by Chen et al. [7], where during the downlink phase energy is scavenged by the source and relay from the advanced access point and they also assist the source's information transmission during the up-link phase. In [8], ergodic capacity and the outage probability of a multi-antenna relay system under the impact of co-channel interference (CCI) have been investigated, where the exploitation of CCI is considered as a promising source of wireless energy transfer. According to aforementioned studies, in EH relay systems, the operation mode of the wireless powered terminals [2, 3] or the scheduling of relay nodes [7, 8] is not similar to that of traditional cooperative systems. As one of main reason that the scavenged energy at EH receiver relies solely on the instantaneous channel gains from the source's RF radiation, and then this scheme leads the system performance can be greatly enhanced by the dynamic exploitation of wireless fading variance in RF powered systems. By proposing the cooperative role which is dynamically applied in of each node of the conventional cooperative relaying systems, results in a substantially better diversity gain and hence, this scheme was also so-called as a new opportunistic role selection (ROSE) strategy [9].

Another line of research on energy harvesting is that investigation on throughput optimization for wireless communications has been extensively studied in volumes of literature. For example, joint power splitting coefficients and antenna selection scheme were taken into considered system model as in [10], where multiple antennas are provided for the relay to carry out energy harvesting process at the source node. As a result, the highest portion of power splitting and the best antenna can be chosen that optimize the achievable rate. Beside that, the optimal power allocations maximizing the throughput was obtained in [11] when different parameters of harvested energy and channel state information is prior known. Helpful practical insights into AF relaying using energy harvesting have been gained in the above-mentioned studies. However, the impact of interference was neglected. The investigation in [12] examined the influence of the source's interference and further using game theory to optimize the power splitting factors. Moreover in literature, energy harvesting transmitter and throughput optimization were investigated under a specific constraint and static channel condition. Then in [13–15], they solved problems of optimal throughput in terms of different fading and multiple access channels. Furthermore, the different nodes in relaying can be cooperated to produce throughput optimization in energy harvesting enabled communications. In [15], throughput maximization is explored for the orthogonal relay channel which evaluating at source and relay nodes where depends on energy harvesting capability. While [16] presented a bi-directional relaying network with energy harvesting enabled nodes and introduced the optimal pre-defined energy collecting strategies in order to obtain end-to-end throughput maximization.

Focusing EH efficiency, the authors in [16] presented that harvest-use relaying protocol in order to evaluate a trade-off between EH time and information processing time which applied in amplify-and-forward (AF) full-duplex (HD) relaying. More importantly, they investigated the optimal time splitting fraction which is expressed as an optimization algorithm and a closed-form is given with an approximation. However, they only solved optimal problem of instantaneous throughput while most of wireless relaying systems require the delay assisted throughput evaluation. In addition, the throughput performance of relaying network are evaluated in scenarios of one-way or two-way mode and half-duplex or full-duplex in various previous works as [17–19]. The optimal fraction of time/power in energy harvesting has not addressed carefully. In a energy harvesting enabled relaying system, both information processing and energy transfer are required; hence, how to achieve the best trade-off in energy harvesting fraction allocation between outage probability, optimal throughput, and percentage of harvested power has become an interesting open problem. In general, a comprehensive survey shown that a few works considering the closed-form expression of optimal power splitting coefficient in energy harvesting enabled relaying networks. To fill such a gap, this paper investigate such a trade-off by focusing on the power-splitting design at the energy constraint relay. To the best of the authors' knowledge, the channel state information-based power-splitting fraction allocation has not been explored in the literature. As important achievement, this paper proposes an online solution for the optimal throughput under consideration of balancing operation requirements between the energy harvesting and information processing phases. In particular, this investigation considers a PS protocol based wireless relay network can collect energy and amplify-and-forward (AF) scheme is deployed to forwarding signal to destination. It worth noting that the relay produce the capability of adjustable processing the power splitting ratio for satisfying roles of processing simultaneous information transmission and energy harvesting (EH) with respect to optimal outage probability and maximal delay-limited throughput. It is assumed that the knowledge of channel state information (CSI) at the relay can be obtained at relay for exact selection of dynamic power splitting policies.

The rest of this paper is organized as following sections. The energy harvesting transmission architecture is recommended as the system model in Sect. 2. In addition, Sect. 3 presents the expression of optimal power splitting coefficients of energy harvesting in three transmission modes including instantaneous throughput, delay-limited throughput and delay-tolerant throughput. Simulation results are verified and more explanations are presented in Sect. 4. Eventually, a conclusion will be drawn in Sect. 5.

2 System Model

Let's consider a wireless relaying network, as illustrated in Fig. 1, which consists one source node S, a wireless-powered relay node R, and one destination node D build a network topology. These nodes can be or not be co-located in the same small-cell which belongs to different area in K-tier cellular networks (heterogeneous networks). It is assumed that it does not exist of direct transmission link between S node and the D node and result in design of intermediate relay assisting the transmission of S node to D node. In such model, the intermediate relay is designed as energy constrained node and the power splitting-based relay protocol is employed as reference model in the previous work [1], i.e., a relay node first collect energy from the

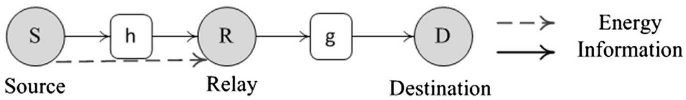

Fig. 1 The system model for energy harvesting-aware relaying network

ambient RF signals sent by the source node known as down-link (DL) (information contain energy signal), and then transmits the useful information signal (pure information) intending to the destination node. For simplicity in implementation and advantage in performance evaluation, the AF relaying scheme is applied in this system model due to its simple principle. It is assumed that both channels in the two-hop of the relaying network are flat block fading, hare means that the channel coefficients are assigned a constant value during each block, but can vary from one to another. To obtain wireless fading channels at the every receivers, the ideal training pilot-based channel estimation is deployed and resulting in the receiver at the relay can extract perfect channel state information (CSI) transmitting together with a dedicated channel which help system to examine the optimal power splitting coefficient of given energy harvesting protocol.

During the first time slot processing stage, the source node broadcasts both information and energy signals, denoted as $s(t)$ which is transmitted at time index t, and illustrates an arbitrary complex random signal. It can be denoted the transmitted power of source node as P. In this study, the distance of the link $S-R$, and the next link $R-D$ are represented by d_1, d_2 respectively and m is the path loss exponent. The quasi-static block-fading channel gains from the link $S-R$ and the link $R-D$ are denoted by h and g, respectively. These channels are assumed as constant channel over the block time T and their characterization are as independent and identically distributed (i.i.d.) and following well-known Rayleigh distribution.

In PS energy harvesting protocol, half of the two-slot scheme, $T/2$ is assigned for the first hop transmission (simultaneous energy and information transmission) and the last part, $T/2$ is assigned for information transmission in the last hop. Considering the first half of the two-slot time, the percentage of the harvested signal as illustration in Fig. 2, βP is used for the capability of wireless energy harvesting and the remaining received power, $(1-\beta)P$ is equipped to assist the source to relay information processing, in which $0 < \beta < 1$. It is noted that the power splitting coefficient selection of β in the harvesting energy pahse at the energy constraint R node affects both the outage probability and achievable throughput when we evaluate performance of the destination node. After harvesting phase, the relay consumes to forward the source's signal to the destination.

Based on PS architecture, the sampled base-band signal, $y_R(t)$, at the input of base band processor is given by

$$y_R(t) = \sqrt{\frac{P(1-\beta)}{d_1^m}} h s(t) + n_R(t), \tag{1}$$

where $n_R(t)$ is the overall noise at relay and it is assumed as the Gaussian distribution with zero mean and variance σ_R^2.

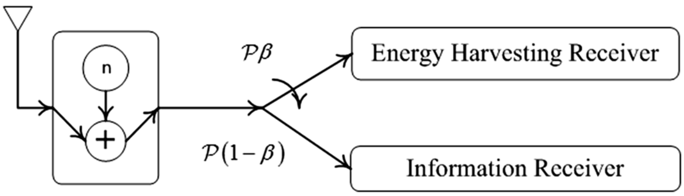

Fig. 2 Energy harvesting architecture based on PS

In the next phase, Gy_R is amplify version of the received signal to transfer to by the destination node D through the fading channel g. The corresponding sampled received signal at the concerned destination, $y_D(k)$ is given by

$$y_D(k) = \frac{1}{\sqrt{d_2^m}} gGy_R(k) + n_D(k), \tag{2}$$

In AF scheme, the relay amplifies the received signal with factor of G which defined as

$$G^2 = \frac{\mathrm{P}_R}{\frac{(1-\beta)P|h|^2}{d_1^m} + \sigma_R^2} \tag{3}$$

In energy harvesting enabled relaying network, the transmitted power assigned for the relay node, P_R is expressed as

$$P_R = \frac{\eta P|h|^2\beta}{d_1^m} \tag{4}$$

Next, the received signal at the destination can be expressed by

$$\begin{aligned} y_D &= \frac{\sqrt{\beta(1-\beta)\eta|h|^2}Phgs(k)}{\sqrt{P|h|^2(1-\beta)+d_1^m\sigma_R^2}\sqrt{d_1^m d_2^m}} + \\ &\frac{\sqrt{\beta\eta P|h|^2}gn_R(k)}{\sqrt{(1-\beta)P|h|^2+d_1^m\sigma_R^2}\sqrt{d_2^m}} + n_D(k) \end{aligned} \tag{5}$$

Thus, the end-to-end signal-to-noise ratio (SNR) at the destination node can be calculated by

$$SNR_D = M/N \tag{6}$$

in which, $M = \eta P^2|h|^4|g|^2\beta(1-\beta)$, $N = \beta\eta P|h|^2|g|^2 d_1^m\sigma_R^2 + P|h|^2 d_1^m d_2^m \sigma_D^2(1-\beta) + d_1^{2m} d_2^m \sigma_R^2\sigma_D^2$.

It is obviously to see that SNR_D depends on the value of β. As confirmation in previous work [1], power splitting factor β affects the system performances drastically. In the next section, the motivation of this work is that discovering the open problem that how to assign proper power splitting ratio in order to achieve the maximal throughput performances. Normally, the outage probability criteria at the destination is used to indicate the system performances. Interestingly, SNR_D is examined as the function of average channel gains related h and g and hence the relay has precise chance to adjusting its harvested power fraction which belongs to the channel state, and introduce the outage performance and throughput with perfect optimization. Based on the available knowledge of CSI at the relay, this paper proposes dynamic harvesting power allocation policy to study the optimal power splitting.

3 Dynamic Harvesting Power Allocation Policy

In this study, the power splitting fraction used for simultaneous information and energy processing during the energy harvesting phase is required to calculate in case of the channel quality is assumed well-known to the receiver. In such case, the online adjusted energy harvesting policy indicated that if feedback bit related energy harvesting is activated, the harvested power allocation coefficient in the transmitter can be adaptively assigned under assistance of the channel state information. Here, this study considers such an adaptive energy harvesting design with the pre-defined value of β which optimally chosen in every block of data frame.

In this section, considering the scenario where harvested power can be first computed in the relay and then performs optimal throughput. This work first characterize the optimal throughput with selected power splitting fraction in three different transmission circumstances, namely instantaneous transmission, delay-limited transmission and delay-tolerant transmission. These throughput performance evaluations are investigated under impacts of the optimal power splitting of PS scheme.

3.1 Instantaneous Transmission

Considering instant SNR to estimate system performance, the instantaneous throughput is expressed by

$$\tau_I = \log_2 (1 + M/N) \tag{7}$$

The optimal power splitting ratio β^* could be determined by solving the following optimization problem

$$\begin{aligned} &\beta^* = \arg\max_{\beta} \tau_I(\beta) \\ &s.t. \quad 0 < \beta < 1 \end{aligned} \tag{8}$$

Proposition 1 *The optimal β_I corresponding with maximum instantaneous throughput is given by*

$$\beta_I = \frac{-\left(P\lambda_h d_1^m d_2^m \sigma_D^2 + d_1^{2m} d_2^m \sigma_R^2 \sigma_D^2\right) + \sqrt{\Delta_1}}{\eta P\lambda_h \lambda_g d_1^m \sigma_R^2 - P\lambda_h d_1^m d_2^m \sigma_D^2} \tag{9}$$

where

$$\begin{aligned} \Delta_1 = &\left(P\lambda_h d_1^m d_2^m \sigma_D^2 + d_1^{2m} d_2^m \sigma_R^2 \sigma_D^2\right) \\ &\times (\eta P\lambda_h \lambda_g d_1^m \sigma_R^2 - P\lambda_h d_1^m d_2^m \sigma_D^2 \\ &+ P\lambda_h d_1^m d_2^m \sigma_D^2 + d_1^{2m} d_2^m \sigma_R^2 \sigma_D^2) \end{aligned} \tag{10}$$

For simplicity in notation, we denote $\lambda_h = E\left\{|h|^2\right\}$, $\lambda_g = E\left\{|g|^2\right\}$ and in which $E\{.\}$ stands for expectation operation. It worth noting that we evaluate the average value of SNR and corresponding optimal coefficient.

Proof It is easy to show that the second derivative of τ_I with respect to β and it is confirmed that it is strictly smaller than zero $\frac{d^2\tau_I}{d\beta^2} < 0$.

Interestingly, τ_I is a concave function with respect to β and hence a unique optimal β_I which maximizes instantaneous throughput exists, and can be computed by solving

$$\frac{d\tau_I}{d\beta} = 0 \tag{11}$$

This completes the proof. □

Based on Proposition 1, it can seen clearly that the knowledge of channel state information (CSI) at the relay is more importantly in energy harvesting scenario, and results in the optimal dynamic power splitting policies with full CSI are required. These CSI values can be known at relay node and feedback information from destination is need be deployed in the proposed policy. Through simulations, the power allocation proposed policy indeed can improve the outage performances and then the throughput as the following subsection.

3.2 Delay-Limited Transmission

In case of delay-limited transmission, the source transmits at a constant rate R_0 (bits/s/Hz), and outage performance is existed under circumstance of the random fading of the wireless channels. To evaluate performance, this paper first calculates the outage probability which is defined as

$$P_{out} = \Pr\left\{SNR_D < \gamma_0\right\} \tag{12}$$

where $\gamma_0 = 2^{R_0} - 1$. Next, the average throughput can be calculated as

$$\tau_{DL} = \frac{R_0}{2}\left(1 - P_{out}\right) \tag{13}$$

It is worth noting that the given the throughput related to the outage expressions presented in [1] does not admit a closed-form solution for solving the optimization problem of power splitting coefficient of PS scheme. As a result, the authors in [1] efficiently solved via numerical calculation. Motivated by the limitation of results in [1], for obtaining power splitting of PS protocol, this study first introduces the following key result:

Proposition 2 *Regarding on the PS protocol, we investigate the outage probability in delay-limited transmission mode of the system can be expressed as*

$$P_{out} = 1 - e^{-\frac{(\beta\eta\lambda_g d_1^m N_0 + d_1^m d_2^m N_0(1-\beta))\gamma_0 + \sqrt{\Delta_2}}{2\eta P\lambda_g\beta(1-\beta)\Omega_h}} \tag{14}$$

where

$$\begin{aligned}\Delta_2 = &\left[\left(\beta\eta\lambda_g d_1^m N_0 + d_1^m d_2^m N_0(1-\beta)\right)\gamma_0\right]^2 \\ &+ 4\eta P\lambda_g\beta(1-\beta)d_1^{2m}d_2^m N_0^2\gamma_0 d_1^{2m}d_2^m\sigma_R^2\sigma_D^2\gamma_0\end{aligned} \tag{15}$$

It is noted that $\lambda_g = E\left\{|g|^2\right\}$

Proof See in the "Appendix" □

In order to find optimal performance in data transmission, the optimal power splitting coefficients for maximum throughput τ_{DL} is considered as hard problem. Interestingly, this study presents an alternative expression which requires a simple approximation below in case of high SNR.

$$h_2 \approx \frac{\left(\beta\eta\lambda_g d_1^m \sigma_R^2 + d_1^m d_2^m \sigma_D^2 (1-\beta)\right)\gamma_0}{\eta P \lambda_g \beta (1-\beta)} \tag{16}$$

As a result, the throughput in delay-limited transmission mode can be given by

$$\tau_{DL} = \frac{R_0}{2}\left(1 - P_{out}\right) = \frac{R}{2}\left(e^{-\frac{\left(\beta\eta|g|^2 d_1^m N_0 + d_1^m d_2^m N_0 (1-\beta)\right)\gamma_0 + \sqrt{\Delta_2}}{2\eta P |g|^2 \beta(1-\beta)\Omega_h}}\right) \tag{17}$$

Proposition 3 *The optimal β in delay-limited mode is given by*

$$\beta_{DL} = \frac{-\sigma_D^2\gamma_0 + \sqrt{\sigma_D^2\gamma_0 + \left(\eta\lambda_g\sigma_R^2 - \sigma_D^2\right)\sigma_D^2\gamma_0^2}}{\left(\eta\lambda_g\sigma_R^2 - \sigma_D^2\right)\gamma_0} \tag{18}$$

Proof The optimal β can be calculated by the equation

$$\frac{d\left(\frac{\left(\beta\eta\lambda_g d_1^m \sigma_R^2 + d_1^m d_2^m \sigma_D^2 (1-\beta)\right)\gamma_0}{\eta P \lambda_g \beta(1-\beta)}\right)}{d\beta} = 0 \tag{19}$$

This ends of the proof. □

3.3 Delay-Tolerant Transmission

Different with delay-limited mode, the source node can transmits at fixed rate below the ergodic capacity in delay-tolerant transmission mode. More specifically, the length of codeword is longer compared to the block time. As a result, codeword over entire realizations of fading channels is transmitted which conditioning on the ergodic capacity considered as an approximate measurement. Hence, the throughput in delay-tolerant transmission mode can be computed by [1]

$$\tau_{DT} = \int_0^\infty \Phi e^{\Phi\gamma} \log_2(1+\gamma)\,d\gamma, \tag{20}$$

where

$$\Phi = \frac{\left(\beta\eta\lambda_g d_1^m \sigma_R^2 + d_1^m d_2^m \sigma_D^2 (1-\beta)\right)}{\eta P \lambda_g \beta(1-\beta)} \tag{21}$$

Proposition 4 *Thanks to solve* $\frac{d\Phi}{d\beta} = 0$, *the optimal* β *in delay-tolerant mode is similar with delay-limited and is given by*

$$\beta_{DT} = \frac{-\sigma_D^2\gamma_0 + \sqrt{\sigma_D^2\gamma_0 + \left(\eta\lambda_g\sigma_R^2 - \sigma_D^2\right)\sigma_D^2\gamma_0^2}}{\left(\eta\lambda_g\sigma_R^2 - \sigma_D^2\right)\gamma_0} \tag{22}$$

Proof Due to the expression of throughput in delay-tolerant a concave function of $\boldsymbol{\Phi}$, which results in the maximum throughput is equivalent with finding the optimal of $\boldsymbol{\Phi}$ can be derived. This interesting evident can be confirmed in the simulation result in the next section.

This ends of the proof. □

Remark 1 the derived expressions of outage probability and corresponding throughput performance are a function of the EH power splitting fractions β. However, the solution for closed-form expressions of power fraction are calculated under condition on prior known information of channel and feedback channel/controlling channel. Moreover, in this work, it is assumed that the CSI is available at the relay and destination node. If the CSI of each channel is sent to the relay in signal block processing time, the proposed protocols can be made adaptive by changing the energy harvesting power splitting ratios according to the channel conditions. Besides that, the throughput relies on the other parameter such as noise, transmit power, energy conversion efficiency, etc. As a result, several scenarios can be illustrated to validate through simulations in the next section.

4 Numerical Results

This section presents some numerical aims to evaluate the analytical expressions which are considered in the previous section. In particular, this paper will discuss the achievable throughputs in corresponding transmission modes for the considered PS energy harvesting scheme. Unless otherwise stated, the source transmission fixed rate is assigned to be $R_0 = 2$ (bps/Hz) and the end-to-end SNR threshold is given by $SNR_0 = 2^{R_0} - 1 = 3$, source transmission power, $P = 1$ J/s. Related the channel, the path loss exponent is set to be $m = 3$, and the distance of each hop d_1 and d_2 are normalized to unit value. The energy harvesting efficiency is set to be $\eta = 1$, equal AWGN noise terms at R and D are set to be $\sigma_R^2 = \sigma_D^2 = 0.02$ for simple calculation. The channel means of the dual-hop channel gains are set as $\Omega_h = \Omega_g = 1$. In this section, the main problem on how the relay node dynamically adjusts the power splitting ratio of information transmission and energy harvesting is evaluated to obtain the optimal outage performance.

Figure 3 examines the analytical results for the outage probability versus transmit power of source node. This result need be used 20,000 random channel realizations as Monte-Carlo simulation. As can be seen that both the case of fixed power splitting ratio and the analytical optimal expressions (defined in previous section) for the outage probability are evaluated. As shown in Fig. 3, the analytical and simulation results match in the entire SNR region with the fixed. The results verify the analytical problem which can be confirmed the proposed power splitting scheme in delay-limited transmission mode achieve the better performances than all the schemes with fixed β.

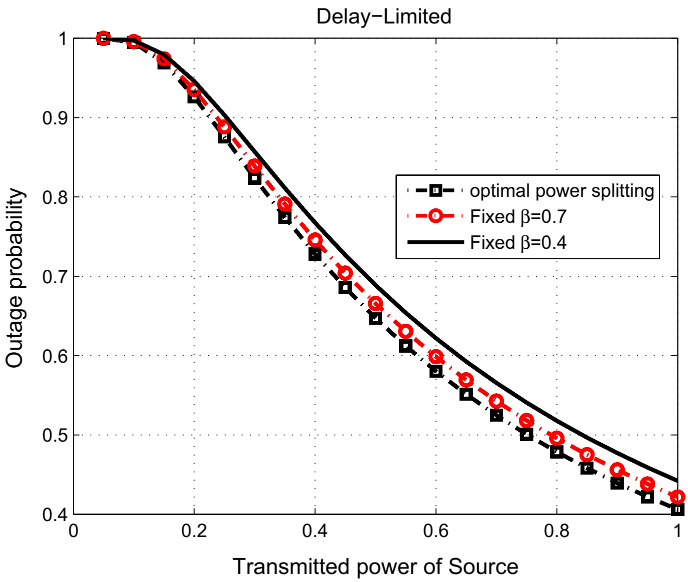

Fig. 3 Outage performance versus transmit power of source

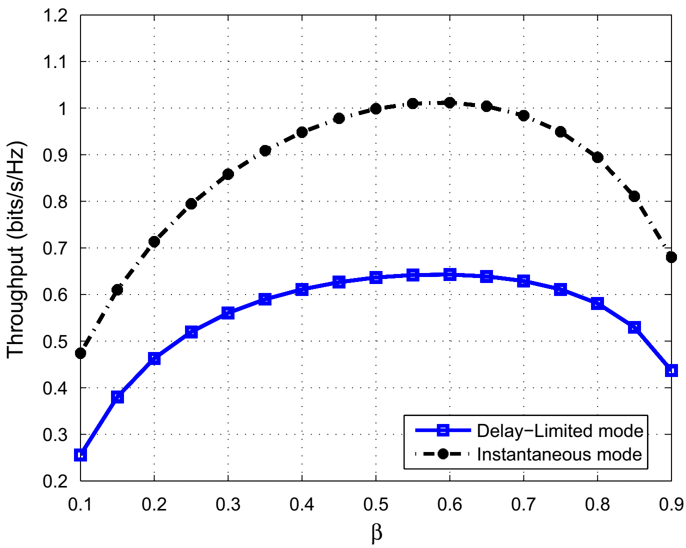

Fig. 4 Throughput at the destination node with in delay-limited and Instantaneous mode versus different β

Figure 4 depicts the impact of β on harvested energy for the optimal throughput for the two transmission modes including delay-limited and instantaneous modes. It can be seen that the value of throughput in delay-limited mode increase dramatically when β climbs from 0 to optimal value (i.e., β is approximate 0.6). However, there is a decrease in the values of throughput due to the trade-off between information transmission and energy transfer processing. In particular, the value of throughput of delay-limited mode is slight fall down as β greater than the given optimal value. In addition, we can see that the value of throughput in instantaneous mode is randomly different compared with delay-limited transmission mode. It is worth noting that the optimal of β in case of instantaneous mode is changed and depends on varying characterization of fading channels in each simulation run.

In Fig. 5 plots the optimal throughput in delay-limited mode for different values of the source transmission rate, R_0 bits/s/Hz. The result confirms that the optimal throughput increases as rate increases from 1 to 2 but then starts decreasing for larger values of source transmission rate. The reason is that throughput depends on this rate and thus at relatively low transmission rates, but the throughput decreases as requiring high transmission rate, i.e., throughput is pushed to the floor value with rate is greater than 5 bits/s/Hz.

In Fig. 6 depicts the value of throughput in delay-limited mode when the value of noise changes from 0.06 to 0.02. The throughput performance surely is considered more improve as declining noise term. This is due to the fact that for calculations of SNR, outage and throughput are related to the received signal, while these noise terms all affect to the received signal as illustration in previous expressions.

In Fig. 7, we can see that the results of optimal power splitting fraction in delay-limited mode (denoted by DL) and delay-tolerant (denoted by DT) are the similar value which are also resulted by mathematical expression. This confirms that it is important to differentiate role of the energy harvesting and information processing phases when designing the power-splitting policy which leads to good throughput performance.

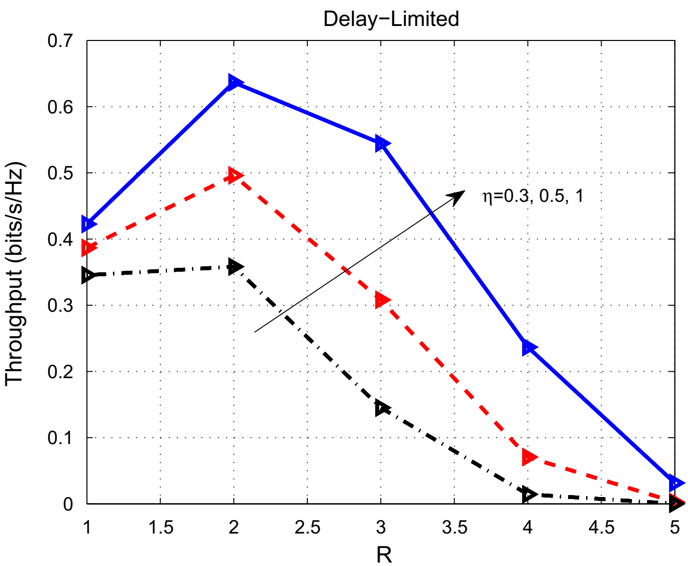

Fig. 5 Throughput performance under impacts of energy conversion efficiency and transmission rate

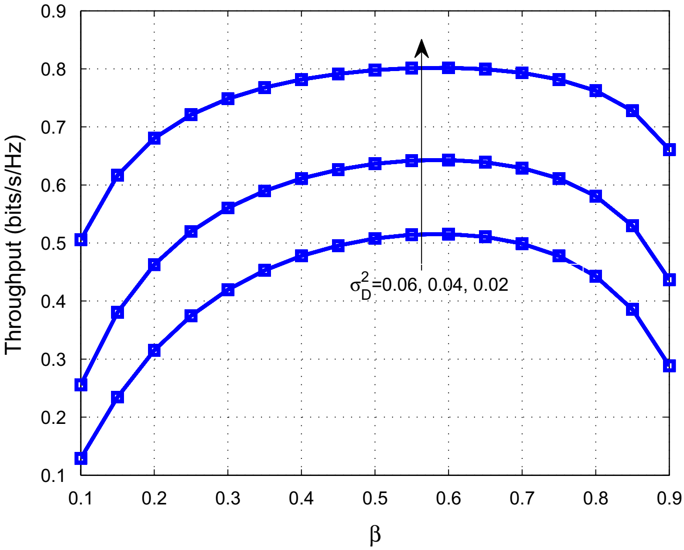

Fig. 6 Throughput performance versus varying noise at destination

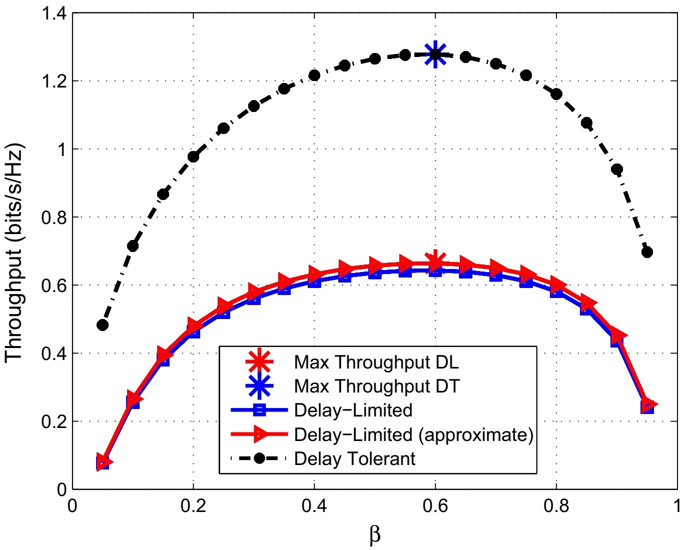

Fig. 7 Findings of optimal power splitting coefficients

5 Conclusion

In this study, full CSI-based power splitting schemes have been proposed for the AF relaying network with wireless information and power transfer. The power splitting ratio has been optimized to minimize outage probability and has considered under several effects. Through simulations, it is confirmed that both proposed power splitting schemes corresponding different transmission modes outperforms the fixed power splitting scheme. It is also found that the best throughput performance is obtained in delay-tolerant mode while the same optimal value of energy power ratio for both delay-limited and delay-tolerant mode. Finally, the proposed energy harvesting policy and its optimal solution is applicable to future wireless networks, such as the small cell communication systems.

Appendix

Proof of Proposition 2 The outage probability can be computed by

$$\Pr\left\{\frac{\eta P^2|h|^4|g|^2\beta(1-\beta)}{P|h|^2L + d_1^{2m}d_2^m\sigma_R^2\sigma_D^2} < \gamma_0\right\} \tag{23}$$

where $L = \beta\eta|g|^2 d_1^m\sigma_R^2 + d_1^m d_2^m\sigma_D^2(1-\beta)$. It can be re-expressed by

$$\Pr\left\{\left(|h|^2 - h_1\right)\left(|h|^2 - h_2\right) < 0\right\} \tag{24}$$

in which h_1 and h_2 are outcomes of the function below

$$\begin{aligned} &\eta P^2|h|^4|g|^2\beta(1-\beta) - d_1^{2m}d_2^m\sigma_R^2\sigma_D^2\gamma_0 \\ &-P|h|^2\left(\beta\eta|g|^2d_1^m\sigma_R^2 + d_1^m d_2^m\sigma_D^2(1-\beta)\right)\gamma_0 = 0 \end{aligned} \tag{25}$$

and h_1 and h_2 are determined by

$$h_1 = (B - \sqrt{B^2 + 4AC}/(2A) \tag{26}$$

$$h_2 = (B + \sqrt{B^2 + 4AC}/(2A) \tag{27}$$

where

$$A = \eta P^2|g|^2\beta(1-\beta) \tag{28}$$

$$B = P\left(\beta\eta|g|^2d_1^m\sigma_R^2 + d_1^m d_2^m\sigma_D^2(1-\beta)\right)\gamma_0 \tag{29}$$

$$C = d_1^{2m}d_2^m\sigma_R^2\sigma_D^2\gamma_0 \tag{30}$$

Due to $h_1 < 0$, the given outage probability can be rewritten as

$$P_{out} = \Pr\left\{0 < |h_S|^2 < h_2\right\} = F_{|h_S|^2}\left(h_2\right) \tag{31}$$

$$F_{|h_S|^2}\left(h_2\right) = 1 - e^{-\frac{h_2}{\Omega_h}} \tag{32}$$

Thus, we obtain new expression as

$$F_{|h_S|^2}\left(h_2\right) = 1 - e^{-\frac{P\left(\beta\eta|g|^2 d_1^m \sigma_R^2 + d_1^m d_2^m \sigma_D^2 (1-\beta)\right)\gamma_0 + \sqrt{\Delta_2}}{2\eta P^2 |g|^2 \beta(1-\beta)\Omega_h}} \tag{33}$$

This is end of Proof of Proposition 2 by averaging value of channel gain of *h*.

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Dinh-Thuan Do was born in Tuy Hoa City, Vietnam, on July 5th, 1980. He received B.Sc. degree in Electronics and Communications Engineering, M.Sc. and Ph.D. degrees in Electrical Engineering from the Vietnam National University (HCMC-VNU) in 2003, 2007, and 2012 respectively. From September 2009 to September 2010, he was a visiting Ph.D. student at the Wireless Communications Lab (National Tsing Hua University-NTHU), Hsinchu City, Taiwan. Prior to joining academia, he worked as senior engineer at VinaPhone Mobile Network (VNPT) since 2003 until 2009. He was a chair of Communication Engineering Department, Ton Duc Thang University, Ho Chi Minh City since 2011. He has been awarded as excellent young researcher at Ton Duc Thang University. Dr. Thuan was the recipient of the 2015 Golden Globe Award by Ministry of Science and Technology. He is currently Assistant Professor at the Wireless Communications & Signal Processing Lab (WICOM LAB). He also serves as Associate Editor of Bulletin of Electrical Engineering and Informatics Journal (SCOPUS).