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Simultaneous wireless information and power transfer for relay assisted energy harvesting network

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Abstract The simultaneous wireless information and power transfer in an energy harvesting system is investigated, where a relay is self-sustained by harvesting radio-frequency (RF) energy from the transmitter and multiple user devices are distributed according to a homogeneous Poisson point process. A joint time switching and power splitting protocol for relay-assisted transmission is proposed, in which each time slot is split into two stages. In the first stage, the relay utilizes a portion of received RF signal power for energy harvesting and the remaining power for information processing. In the second stage, information is delivered from the relay to its closest destination node with the harvested energy. The outage probability, network throughput and energy efficiency are derived and analyzed in closed form. On this basis, the optimal power splitting and time switching ratio which maximizes network throughput is obtained. Simulation results are also provided to validate our theoretical analysis.

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1 Introduction

Energy harvesting from the ambient environment is a promising technique to prolong the operation of energy constrained wireless networks as well as to improve the energy efficiency [1]. Due to the inherent limitations of some representative renewable energy sources such as wind and solar, energy harvesting from radio-frequency (RF) signals has drawn widespread attention recently with its capability to generate convenient electricity supplies [2, 3]. RF signal energy harvesting is anticipated to play a significant role in battery replacement and system operation cost reduction in both civil and military applications, especially for systems with a large number of nodes distributed in inaccessible areas.

RF signals transmitted by wireless devices can transport on-demand wireless information and deliver energy concurrently. Therefore energy harvesting and information reception can be performed using the same RF signal. This is referred to as simultaneously wireless information and power transfer (SWIPT) approach [4]. With SWIPT, the energy of RF signal can be used effectively for the self-sustained operation of wireless devices. In practice, signal from the source may find it hard to reach the destination directly due to long propagation distance or severe shadowing. In this case, relay can help to forward the signal to the destination and extend the range of communication. With the concept of SWIPT, relay can both harvest energy and receive information from the signal radiated by the source [4]. This makes it possible to eliminate dedicated power supply for relays and reduce system cost drastically.

In this paper, we consider a network with energy harvesting powered relay, which is illustrated in Fig. 1. The network has one access point (AP) which serves as the source of information and energy, one energy-constrained relay which harvests energy from the signal transmitted by the AP and forwards the information to the user devices. There are also multiple user devices in the network which are the destinations of source transmission and distributed according to a homogeneous Poisson point process (HPPP) [5, 6]. In this network, time is divided into equally sized segment called slot.

We design a protocol named joint time switching and power splitting (JTPS) to schedule transmission in this network. JTPS partitions each slot into two stages, namely, receiving stage and transmission stage respectively. In the receiving stage, a portion of the signal energy received by the relay node is used for energy harvesting while the remaining part is utilized for information processing. In the transmission stage, information is retransmitted from the relay to its nearest destination node. The theoretical performance metrics of JTPS including outage probability, network throughput and energy efficiency are derived in closed form as a function of power splitting ratio and time switching ratio. In addition, network throughput is maximized by jointly optimizing power splitting ratio and time switching ratio. We also characterize the throughput of an ideal scenario [7–9], where the relay is capable of extracting information and harvesting energy from the same part of received energy. Simulations are conducted to

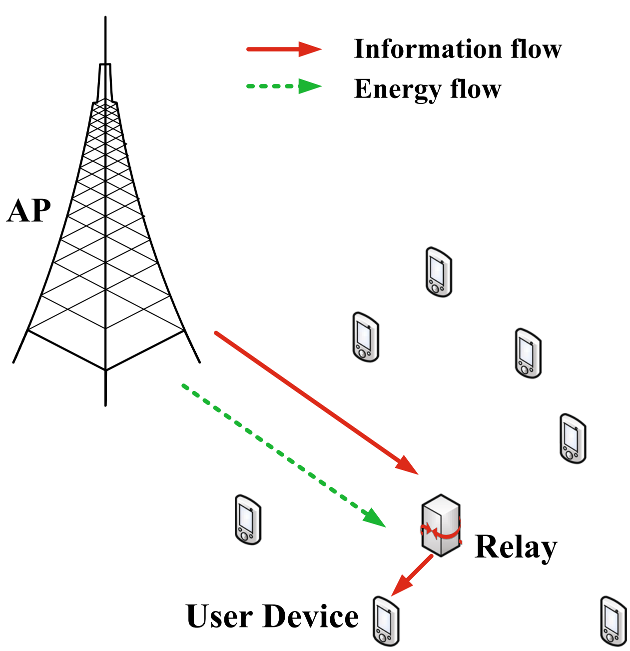

Fig. 1 System model with SWIPT

validate our theoretical analysis and compare our JTPS protocol with existing protocols.

1.1 Related work

The dual utilization of RF signals for delivering information as well as transporting energy attracts widespread attention recently. A number of researches concerning SWIPT have been conducted [7–14]. Varshney first proposes the idea of SWIPT and deals with a tradeoff between energy harvesting and information transmission over a single noisy line [7]. Popovski et al. [9] consider a two-way channel under a simple binary on-off signaling model with SWIPT. Moreover, the aforementioned work [7–9] adopts the ideal receiver architecture assumption, in which the receiver can harvest energy and extract information from the same portion of signal energy. However, this assumption cannot be held in practice and the performance of ideal receiver can only be viewed as an upper bound. The more practical assumption is that part of received signal energy is utilized for energy harvesting and the remaining part of received signal energy is used for signal processing. On this basis, power splitting protocol (PSP) and time switching protocol (TSP) are proposed [10–14]. Derrick et al. consider a power splitting receiver in a point to point wireless system, it dynamically splits the received power into two power streams for information decoding and energy harvesting [10]. Luo et al. [11] introduce a time switching receiver architecture in a wireless system with one transmitter and one receiver. In [12], the authors extend the time switching and power splitting protocols to an on-off power splitting policy for a point to point wireless link, which splits the received streams for information decoding and energy harvesting with adjustable power levels. Moreover, Zhao et al. in [13, 14] propose a power splitting optimization algorithm for energy harvesting networks using interference alignment technique.

The concept of SWIPT is particularly suitable for relay assisted energy harvesting system [4]and a lot of researches investigate energy harvesting powered relay with SWIPT [19–21]. It is assumed that the relay node receives and retransmits signal over two different frequency bands and how to schedule signal processing and energy harvesting is the core problem of these systems. To coordinate information transmission and power transfer, time switching based relaying (TSR) protocol allows the relay to switch and utilize either the information receiver or the energy harvester for the received signals at a time, while the received signals are split into two streams for the information receiver and the energy harvester with different power levels in power splitting based relaying (PSR) protocol[4].

In [19], an energy constrained relay is investigated in an amplify and forward (AF) relaying network, which utilizes PSR and TSR to conduct information processing and energy harvesting. Nasir et al. [20] propose an adaptive time switching protocol and extend the work in [19] to both AF and decode and forward (DF) relaying networks. Moreover, Liu et al. [21] consider that a source node transfers information and energy simultaneously over OFDM to a relay node and the relay node adopts PSR to forward information to the destination node. However, there are some limitations in these researches. Firstly, the distances between communicating nodes are determinate, which is not realistic for practical systems where communication happens in a random manner. Secondly, most of the analyses focus on point-to-point system which is oversimplified for practical systems.

Energy efficiency is an important performance metric for energy-constrained energy harvesting system. Existing approaches achieve efficient energy usage by maximizing network throughput while minimizing energy consumption [15, 16]. In [17], the authors consider an orthogonal frequency division multiplexing (OFDM) based system with co-channel interference using power splitting protocol. An iterative algorithm is adopted to maximize energy efficiency. Derrick et al. [18] investigate the downlink of an OFDMA based single input and single output system with SWIPT. The receiver is capable of power splitting with arbitrary splitting ratios. However, the performance is characterized by optimizing power splitting ratio or time switching ratio independently in existing researches, their joint optimization has not been addressed to the best of our knowledge.

1.2 Summary and organization

The main contributions of this paper can be summarized as follows.

1. We propose a more practical scenario, in which relay-assisted energy harvesting system has multiple user devices modeled by independent HPPPs, and the information transferred from the AP to the user devices is amplified and forwarded by the relay node.
2. A joint time switching and power splitting protocol is introduced. Based on the proposed protocol, we derive the outage probability, network throughput and energy efficiency as a function of power splitting ratio and time switching ratio.
3. Network throughput is maximized by jointly optimizing power splitting ratio and time switching ratio.

The remainder of this paper is organized as follows. The system model and performance metrics are introduced in Sect. 2. Section 3 formulates the relationship between the performance metrics and system parameters such as time switching ratio and power splitting ratio. Section 4 analyzes the network throughput of an ideal receiver. Numerical results are presented in Sect. 5. Finally, we conclude the paper in Sect. 6.

2 System model

2.1 Network model

We consider a wireless network illustrated in Fig. 1, which consists of one single-antenna AP named source S, a terminal which acts as an energy constrained relay R and multiple user devices distributed according to a HPPP Θ with density λ. The user devices are the destination of data transfer and denoted as destination node D. We assume there is no direct link between the source and the destination nodes due to path-loss and shadowing. The information is transferred from S to D with the assistance of the relay node. The source is continuously connected to a power supply and the transmission power is P, the relay node has no direct power supply and harvests energy from the RF signal trasmitted by the source. In addition, the relay node has no traffic and is dedicated to forward the information from the source to the destination. Furthermore, we assume the relay node receives and retransmits signals over two different frequency bands.

The propagation channel is modeled as the combination of small-scale Rayleigh fading and large-scale path-loss given by

$$h_{XY} = \tilde{h}_{XY}\sqrt{r_{XY}{}^{-\alpha}}, \tag{1}$$

where $\tilde{h}_{XY} \sim \mathcal{CN}(0, \mu_{XY})$ denotes the channel coefficient from X to Y with $X, Y \in \{S, R, D\}$ $(X \neq Y)$, the channel power gain $\left|\tilde{h}_{XY}\right|^2$ follows an exponential distribution with mean μ_{XY}, r_{XY} denotes the propagation distance between X and Y, and $\alpha > 2$ is the path-loss exponent.

Time is partitioned into slots with duration T. Over each transmission slot, the channel gains remain constant. r_{SR} is the distance between the source S and the relay node R, we denote it as $l = r_{SR}$ for simplicity. Due to the energy constraint, the relay node only transfers the messages from the source to the nearest destination node in each time slot.

An important factor is the distance between the relay node and its nearest destination node, denoted as r. Intuitively, the distances from the relay to other destination nodes must be larger than r. The probability density function (PDF) of r can be derived using the fact that the null probability of a 2-D Poisson process in an area A is $e^{-\mu A}$[22].

$$f_r(r) = e^{-\lambda\pi r^2} 2\pi\lambda r. \quad (2)$$

2.2 Transmission mode

The system adopts a JTPS protocol with relay-assisted transmission and the structure of JTPS protocol is plotted in Fig. 2. Each time slot has a duration of T and is partitioned into two parts. The first part has a duration of τT, where τ is the time switching ratio and $0 < \tau < 1$. In this part of time, a portion of the received power (ρP_{rec}) is utilized for energy harvesting by the relay node and the remaining power ($(1-\rho)P_{rec}$) is used for information processing, ρ is the power splitting ratio $(0 < \rho < 1)$. The second part of the slot has a duration of $(1-\tau)T$ and is used for retransmitting data from the relay node to its nearest destination node using AF mechanism. P_{rec} is the received signal power of the relay node. We assume the power consumed by the hardware and other factors is negligible, that is, all the energy harvested from the source is utilized to deliver data from the relay to the destination.

2.3 Performance metric

In this paper, three performance metrics are considered, including outage probability, network throughput and energy efficiency, and their definitions are given as follows.

Outage probability Outage probability is the probability that a destination node decodes the received data packets unsuccessfully from the source. Specifically, given the signal-to-noise ratio (SNR) and a corresponding SNR target represented by γ, the outage probability can be calculated by

$$p_{out} = \mathbb{P}(\mathrm{SNR} < \gamma). \quad (3)$$

Network throughput Network throughput is the maximum rate the system can achieve under successful transmissions and has a unit of bits/sec (bps). Assume the source transmission rate target is $\Omega = \log(1+\gamma)$, and the total transmission time is t. Consequently, the network throughput is given by

$$C = (1-p_{out}) \cdot \Omega \cdot t. \quad (4)$$

Energy efficiency Energy efficiency of the network is the amount of data successfully transmitted over the amount of utilized energy. Energy efficiency is measured by bps/Joule (bps/J). Denote the total energy consumption as Q_c, the energy efficiency can be written as $EE = C/Q_c$.

The notations used in this paper are summarized in Table. 1.

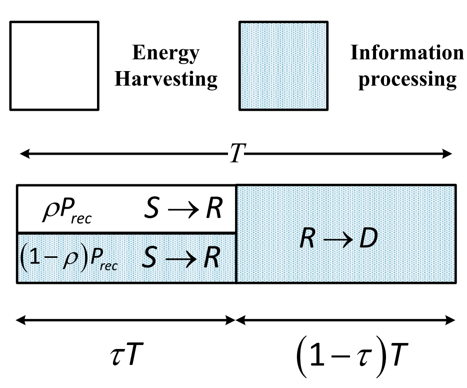

Fig. 2 Transmission structure for JTPS protocol

3 Relay-assisted transmission mode

In this section, we assume that the locations of the destination nodes follow a HPPP denoted as Θ. We firstly derive the outage probability of the JTPS protocol. On this basis, network throughput is maximized by the joint optimization of time switching ratio τ and power splitting ratio ρ.

Table 1 Symbol table

Symbol	Definition
P	Transmission power of the source node
Q_c	The total energy consumption
EE	Energy efficiency
P_r	Transmission power of the relay node
T	The duration of one transmission slot
γ	Signal to noise ratio (SNR) target
ρ	Power splitting ratio
τ	Time switching ratio
h	Rayleigh channel coefficient
r_{XY}	The propagation distance between X and Y
l	The distance between the source and the relay
λ	The density of the distributed users
η	Energy harvesting efficiency
α	Path-loss exponent
ξ	Amplification factor of the relay node
Ω	Transmission rate target
p_{out}	Outage probability
C	Network throughput
$AWGN$	Additive Gaussian white noise
σ_1^2	The variance of the AWGN over the S–R link
σ_c^2	The variance of the AWGN over the R–D link

3.1 Outage probability

According to the JTPS protocol shown in Fig. 2, in the first part of the time slot τT, the received signal energy is split into two parts by the coefficient ρ. Denote the received signal as y_r, $\sqrt{\rho}y_r$ is sent to the energy harvesting receiver, which can collect RF signals and transform them into direct-current (DC) power. The remaining part $\sqrt{1-\rho}y_r$ is sent to information receiver for information processing. Initially, y_r is given by

$$y_r = \sqrt{P}h_{SR} \cdot s(m) + n_a, \tag{5}$$

where $h_{SR} = \tilde{h}_{SR}\sqrt{l^{-\alpha}}$, $s(m)$ is data symbol transmitted by the source, and $\mathbb{E}\left\{|s(m)|^2\right\} = 1$. n_a is the AWGN caused by the receiving antenna of the relay node. Then the energy harvested by the relay node from the source can be given by

$$E_h = \eta\rho P|h_{SR}|^2\tau T, \tag{6}$$

where η $(0<\eta\leq 1)$ refers to the harvesting efficiency.

The information receiver receives the remaining part of signal energy and conducts the processing necessary for forwarding. The sampled signal at the information receiver can be given by

$$y_r(m) = \sqrt{(1-\rho)P}h_{SR} \cdot s(m) + \sqrt{(1-\rho)}n_a + n_b, \tag{7}$$

where n_b is the AWGN caused by signal processing.

For the remaining part of the time slot, the relay node amplifies and forwards the sampled signal to the destination node using the power P_r given by

$$P_r = \frac{E_h}{(1-\tau)T} = \frac{\eta\rho P|h_{SR}|^2\tau}{(1-\tau)}. \tag{8}$$

The amplification factor [23] is

$$\xi = \frac{1}{\sqrt{(1-\rho)P|h_{SR}|^2 + (1-\rho)\sigma_a^2 + \sigma_b^2}}, \tag{9}$$

where σ_a^2 and σ_b^2 are the variances of the AWGN n_a and n_b, respectively.

After amplifying the signal $y_r(m)$, the transmitted signal by the relay node is given by

$$\begin{aligned} x_r(m) =& \sqrt{P_r}y_r(m)\xi \\ =& \frac{\sqrt{P_r}y_r(m)}{\sqrt{(1-\rho)P|h_{SR}|^2 + (1-\rho)\sigma_a^2 + \sigma_b^2}}. \end{aligned} \tag{10}$$

Therefore, the received signal at the nearest destination node $y_d(m)$ can be obtained as

$$y_d(m) = h_{RD} \cdot x_r(m) + n_c, \tag{11}$$

where $h_{RD} = \tilde{h}_{RD}\sqrt{r^{-\alpha}}$, n_c is the overall AWGN at the destination node, and σ_c^2 is the variance of the AWGN n_c. Substituting (7) and (10) into (11), we can derive

$$\begin{aligned} y_d(m) =& \frac{h_{RD}\sqrt{(1-\rho)PP_r}h_{SR}s(m)}{\sqrt{(1-\rho)P|h_{SR}|^2 + (1-\rho)\sigma_a^2 + \sigma_b^2}} \\ &+ \frac{h_{RD}\sqrt{(1-\rho)P_r}n_a + h_{RD}\sqrt{P_r}n_b}{\sqrt{(1-\rho)P|h_{SR}|^2 + (1-\rho)\sigma_a^2 + \sigma_b^2}} + n_c \\ =& \frac{h_{RD}\sqrt{(1-\rho)PP_r}h_{SR}s(m)}{\sqrt{(1-\rho)P|h_{SR}|^2 + \sigma_1^2}} \\ &+ \frac{h_{RD}\sqrt{P_r}n_1}{\sqrt{(1-\rho)P|h_{SR}|^2 + \sigma_1^2}} + n_c, \end{aligned} \tag{12}$$

where we use $n_1 = \sqrt{1-\rho} \cdot n_a + n_b$ to denote the total AWGN at the relay node and $\sigma_1^2 = (1-\rho) \cdot \sigma_a^2 + \sigma_b^2$ is the power of the AWGN. The first term of (12) is the signal part while the second and third terms are noise. The SNR at the destination node is given by

$$\begin{aligned} \gamma_{SRD} =& \frac{\frac{|h_{RD}|^2(1-\rho)PP_r|h_{SR}|^2}{(1-\rho)P|h_{SR}|^2+\sigma_1^2}}{\frac{|h_{RD}|^2P_r\sigma_1^2}{(1-\rho)P|h_{SR}|^2+\sigma_1^2} + \sigma_c^2} \\ =& \frac{|h_{RD}|^2(1-\rho)PP_r|h_{SR}|^2}{|h_{RD}|^2P_r\sigma_1^2 + (1-\rho)P|h_{SR}|^2\sigma_c^2 + \sigma_1^2\sigma_c^2}. \end{aligned} \tag{13}$$

Then, substituting (8) into (13), we have

$$\begin{aligned} &\gamma_{SRD} = \\ &\frac{|h_{RD}|^2(1-\rho)P^2|h_{SR}|^4\eta\rho\frac{\tau}{(1-\tau)}}{|h_{RD}|^2|h_{SR}|^2\eta\rho P\sigma_1^2\frac{\tau}{(1-\tau)} + (1-\rho)P|h_{SR}|^2\sigma_c^2 + \sigma_1^2\sigma_c^2}. \end{aligned} \tag{14}$$

From Sect. 2.3, the outage probability P_{out_1} is

$$P_{out\_1} = \mathbb{P}(\gamma_{SRD} < \gamma). \tag{15}$$

Then we have the following theorem.

Theorem 1 *The outage probability P_{out_1} for the JTPS protocol at the destination node is obtained as*

$$\begin{aligned} p_{out\_1} =& \frac{2\pi\lambda}{\alpha\mu_{SR}}\int_{\frac{\Gamma}{\Phi}}^{\infty}\int_0^{\frac{\Lambda z}{\Phi z^2-\Gamma z}} e^{-\frac{z}{\mu_{SR}}+\lambda\pi y^{-\frac{2}{\alpha}}}y^{-\frac{2+\alpha}{\alpha}}\mathrm{d}y\mathrm{d}z \\ &+ 1 - e^{-\frac{\Gamma}{\Phi\mu_{SR}}}, \end{aligned} \tag{16}$$

where

$$\begin{aligned} \Lambda =& (1-\rho)P\sigma_c^2\gamma, \\ \Phi =& l^{-\alpha}P^2\rho(1-\rho)\eta\frac{\tau}{(1-\tau)}, \\ \Gamma =& P\eta\rho\sigma_1^2\gamma\frac{\tau}{(1-\tau)}, \end{aligned} \tag{17}$$

μ_{SR} is the mean value of the exponential distribution $\left|\tilde{h}_{SR}\right|^2$.

Proof We derive the outage probability p_{out_1} by substituting (14) into (15), and P_{out_1} is given as (18),

$$\begin{aligned}
&p_{out_1}\\
&=\mathbb{P}\left(\frac{|h_{RD}|^2(1-\rho)P^2|h_{SR}|^4\eta\rho\frac{\tau}{(1-\tau)}}{|h_{RD}|^2|h_{SR}|^2\eta\rho P\sigma_1^2\frac{\tau}{(1-\tau)}+(1-\rho)P|h_{SR}|^2\sigma_c^2+\sigma_1^2\sigma_c^2}<\gamma\right)\\
&=\mathbb{P}\left(|h_{RD}|^2<\frac{(1-\rho)P|h_{SR}|^2\sigma_c^2\gamma+\sigma_1^2\sigma_c^2\gamma}{\left||h_{SR}|^4P^2\rho(1-\rho)\eta\frac{\tau}{(1-\tau)}-|h_{SR}|^2P\eta\rho\sigma_1^2\gamma\frac{\tau}{(1-\tau)}\right|}\right)\\
&\overset{(a)}{=}\mathbb{P}\left(|h_{RD}|^2<\frac{(1-\rho)P\left|\tilde{h}_{SR}\right|^2\sigma_c^2\gamma+\sigma_1^2\sigma_c^2\gamma l^{\alpha}}{\left|\left|\tilde{h}_{SR}\right|^4l^{-\alpha}P^2\rho(1-\rho)\eta\frac{\tau}{(1-\tau)}-\left|\tilde{h}_{SR}\right|^2P\eta\rho\sigma_1^2\gamma\frac{\tau}{(1-\tau)}\right|}\right)\\
&\overset{(b)}{=}\mathbb{P}\left(|h_{RD}|^2<\frac{\Lambda\left|\tilde{h}_{SR}\right|^2+\Upsilon}{\left|\Phi\left|\tilde{h}_{SR}\right|^4-\Gamma\left|\tilde{h}_{SR}\right|^2\right|}\right).
\end{aligned}\tag{18}$$

where (a) follows from $h_{SR}=\tilde{h}_{SR}\sqrt{l^{-\alpha}}$, (b) follows from $\Lambda=(1-\rho)P\sigma_c^2\gamma$, $\Upsilon=\sigma_1^2\sigma_c^2\gamma l^{\alpha}$, $\Gamma=P\eta\rho\sigma_1^2\gamma\frac{\tau}{(1-\tau)}$, and $\Phi=l^{-\alpha}P^2\rho(1-\rho)\eta\frac{\tau}{(1-\tau)}$. For simplicity, we consider a high SNR case, the factor $\sigma_1^2\sigma_c^2$ in the denominator of (14) is approximately 0, such that $\Upsilon\approx 0$. Then we have

$$\begin{aligned}
&p_{out_1}\\
&=\mathbb{P}\left(|h_{RD}|^2<\frac{\Lambda\left|\tilde{h}_{SR}\right|^2}{\left|\Phi\left|\tilde{h}_{SR}\right|^4-\Gamma\left|\tilde{h}_{SR}\right|^2\right|}\right)\\
&=\begin{cases}\mathbb{P}\left(|h_{RD}|^2<\dfrac{\Lambda\left|\tilde{h}_{SR}\right|^2}{\Phi\left|\tilde{h}_{SR}\right|^4-\Gamma\left|\tilde{h}_{SR}\right|^2}\right), & \left|\tilde{h}_{SR}\right|^2>\dfrac{\Gamma}{\Phi}\\[2ex] \mathbb{P}\left(|h_{RD}|^2>\dfrac{\Lambda\left|\tilde{h}_{SR}\right|^2}{\Phi\left|\tilde{h}_{SR}\right|^4-\Gamma\left|\tilde{h}_{SR}\right|^2}\right)=1, & \left|\tilde{h}_{SR}\right|^2<\dfrac{\Gamma}{\Phi}.\end{cases}
\end{aligned}\tag{19}$$

The PDF of the exponential variable $\left|\tilde{h}_{SR}\right|^2$ is $f_{\left|\tilde{h}_{SR}\right|^2}(z)=\frac{1}{\mu_{SR}}e^{-\frac{z}{\mu_{SR}}}$.

Recall that the PDF of r can be derived as $f_r(r)=e^{-\lambda\pi r^2}2\pi\lambda r$, by assuming $y=r^{-\alpha}$, i.e., $r=y^{-\frac{1}{\alpha}}$, we have

$$f_y(y)=f_r\left(y^{-\frac{1}{\alpha}}\right)\left|-\frac{1}{\alpha}y^{-\frac{1}{\alpha}-1}\right|=\frac{1}{\alpha}2\pi\lambda y^{-\frac{2}{\alpha}-1}e^{-\lambda\pi y^{-\frac{2}{\alpha}}}.\tag{20}$$

Since $|h_{RD}|^2=\left|\tilde{h}_{RD}\right|^2r^{-\alpha}$, we assume that $\left|\tilde{h}_{RD}\right|^2$ is averaged to 1 for simplicity, thus we have $f_{|h_{RD}|^2}(z)=\frac{1}{\alpha}2\pi\lambda z^{-\frac{2}{\alpha}-1}e^{-\lambda\pi z^{-\frac{2}{\alpha}}}$

Therefore, the approximated p_{out_1} is given by

$$\begin{aligned}
p_{out_1}&=\int_0^{\frac{\Gamma}{\Phi}}f_{\left|\tilde{h}_{SR}\right|^2}(z)\mathrm{d}z\\
&\quad+\int_{\frac{\Gamma}{\Phi}}^{\infty}f_{\left|\tilde{h}_{SR}\right|^2}(z)\mathbb{P}\left(|h_{RD}|^2<\frac{\Lambda z}{\Phi z^2-\Gamma z}\right)\mathrm{d}z\\
&=\int_0^{\frac{\Gamma}{\Phi}}\left(\frac{1}{\mu_{SR}}e^{-\frac{z}{\mu_{SR}}}\right)\mathrm{d}z\\
&\quad+\int_{\frac{\Gamma}{\Phi}}^{\infty}\int_0^{\frac{\Lambda z}{\Phi z^2-\Gamma z}}\left(\frac{1}{\mu_{SR}}e^{-\frac{z}{\mu_{SR}}}\right)\\
&\quad\times\frac{1}{\alpha}2\pi\lambda y^{-\frac{2}{\alpha}-1}e^{-\lambda\pi y^{-\frac{2}{\alpha}}}\mathrm{d}y\mathrm{d}z.
\end{aligned}\tag{21}$$

This ends the proof for Theorem 1. □

3.2 Throughput and energy efficiency

The throughput is characterized by evaluating the outage probability p_{out_1} at a fixed source transmission rate, which is defined as $\Omega=\log(1+\gamma)$. According to Sect. 2.3, network throughput C_1 is obtained as

$$C_1=\Omega\cdot(1-p_{out\_1})(1-\tau)T.\tag{22}$$

Note that when $\tau\to 0$ or $\rho\to 0$, there is little time or power for energy harvesting. Consequently, the energy harvested by the relay node is scarce, and the throughput is low due to large outage probability. On the other hand, when $\tau\to 1$ or $\rho\to 1$, there is little time or power for information transmission. Furthermore, large ρ also results in the poor signal strength at the relay node. When the relay node amplifies the noisy signal and forwards it to the destination node, low throughput is achieved due to little transmission time or large outage probability. Therefore, there is an optimal combination of τ and ρ, which yields the maximum network throughput C_1.

The total amount of energy consumed by the network is utilized to transmit signal by the source, which means $Q_c=P\cdot T$. From the definition in Sect. 2.3, the energy efficiency is given by

$$EE=\frac{\Omega}{P}\cdot(1-p_{out\_1})\frac{1-\tau}{T}.\tag{23}$$

4 Ideal relay receiver

An ideal receiver can conduct signal processing and energy harvesting on the same part of energy [7]. This is, the total received signal energy is utilized both for signal processing and energy harvesting. With this assumption, the harvested energy during the first part of the time slot τT is given as $E_h=\eta P|h_{SR}|^2\tau T$, and the transmission power of the relay node P_r is obtained as

$$P_r = \eta P |h_{SR}|^2 \frac{\tau}{1-\tau}. \quad (24)$$

Similar to (12), we can obtain the expression of the received signal at the destination node by removing the power splitting ratio ρ, which is given by

$$y_d(m) = \frac{h_{RD}\sqrt{PP_r}h_{SR}s(m)}{\sqrt{P|h_{SR}|^2+\sigma_1^2}} + \frac{h_{RD}\sqrt{P_r}n_1}{\sqrt{P|h_{SR}|^2+\sigma_1^2}} + n_c. \quad (25)$$

Using (25), the SNR at the destination node γ_{SRD_1} is given by

$$\gamma_{SRD\_1} = \frac{|h_{RD}|^2 P^2 |h_{SR}|^4 \eta \frac{\tau}{(1-\tau)}}{|h_{RD}|^2|h_{SR}|^2\eta P\sigma_1^2\frac{\tau}{(1-\tau)} + P|h_{SR}|^2\sigma_c^2 + \sigma_1^2\sigma_c^2}. \quad (26)$$

The outage probability p_{out_2} can be analytically calculated as (16) for $\Lambda = P\sigma_c^2\gamma$, $\Phi = l^{-\alpha}P^2\eta\frac{\tau}{(1-\tau)}$, and $\Gamma = P\eta\sigma_1^2\gamma\frac{\tau}{(1-\tau)}$. The throughput at the destination node is given by $C_2 = \Omega \cdot (1 - p_{out\_2})(1-\tau)T$.

5 Numerical results

In this section, numerical results are provided to verify our theoretical analysis and compare JTPS with other protocols including TSR and PSR. Unless otherwise specified, the parameter settings in the simulation are listed in Table 2.

Figure 3 demonstrates the influence of time switching ratio τ and power splitting ratio ρ on network throughput. It can be observed that the maximum throughput $C_1 = 0.2502$ bps is obtained at $\tau = 0.5$ and $\rho = 0.6$. This can be explained by the fact that for extremely small value of ρ and τ, there is less time or less power available for energy harvesting. Consequently, the energy harvested by the relay node is scarce resulting in low throughput due to high outage probability. On the other hand, when the values of τ or ρ are larger than the optimal values, there is less time or less power for information transmission. Moreover, larger ρ also means poor signal strength at the relay node. When the relay node amplifies and retransmits the noisy signal to the destination node, smaller throughput occurs due to larger outage probability at the destination node. Our results can be used to find out the feasible region in the τ-ρ plane for a given desirable throughput thus guiding practical deployment.

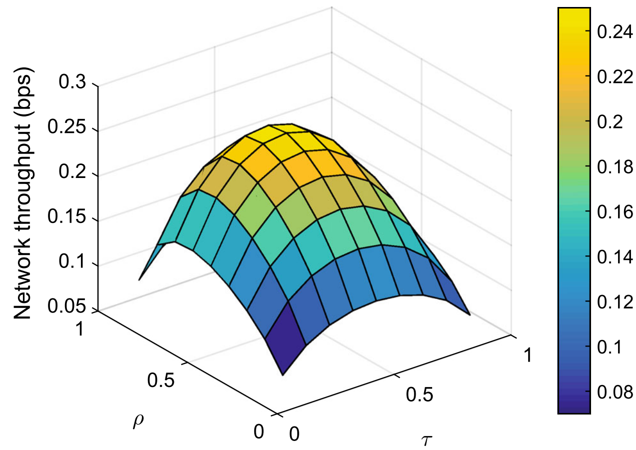

Fig. 3 The network throughput C_1 with different settings of the time switching ratio τ, and the power splitting ratio ρ in the relay-assisted mode

Figure 4 shows the network throughput for JTPS protocol with $0<\rho<1$ at different ρ. It can be observed that the results are consistent with our theoretical analysis. Note that there is an optimal ρ^* yielding the maximum throughput, which is consistent with Fig. 3.

Figure 5 plots the optimal throughput for JTPS protocol, ideal relay receiver, TSR protocol and PSR protocol versus different noise power on R–D link σ_c^2. It is observed that the optimal throughput is inversely proportional to the

Table 2 Parameter settings

Parameter	Setting
Time of transmission slot	$T = 1$ s
Energy harvesting efficiency	$\eta = 1$
Source transmission power	$P = 2$ W
Source transmission rate target	$\Omega = 10$ bps
Path-loss exponent	$\alpha = 4$[a]
The density of the user devices	$\lambda = 0.01$
The power of the AWGN	$\sigma_1^2 = \sigma_c^2 = 0.01$
The mean value of the channel power gain	$\mu_{SR} = 1$
The distance between S and R	$l = 100$ m

[a] It corresponds to a city cellular network environment [24]

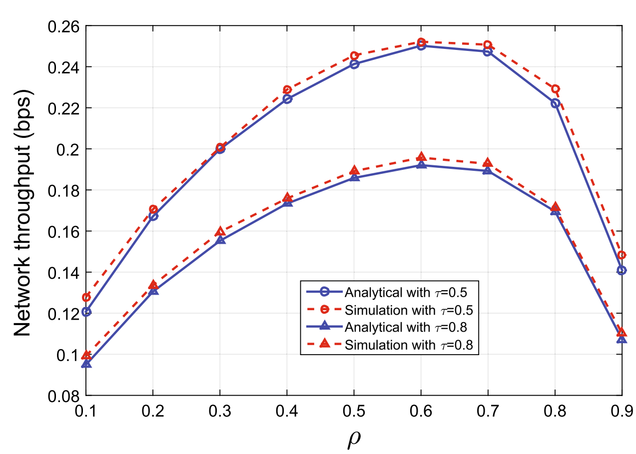

Fig. 4 The network throughput C_1 with different settings of the power splitting ratio ρ in the relay-assisted mode

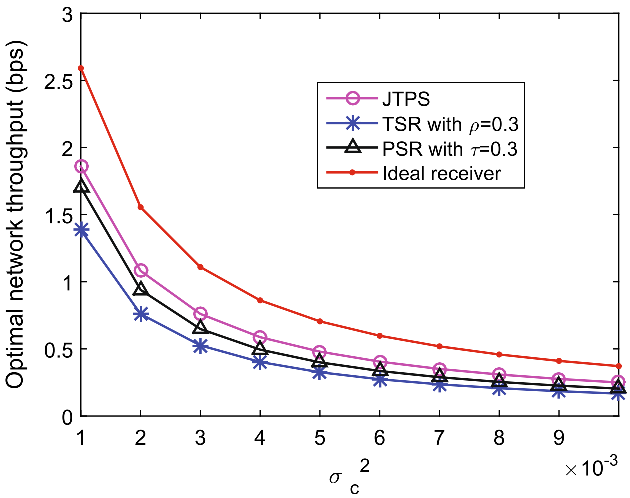

Fig. 5 The optimal network throughput with relay-assisted transmission mode versus the noise power on *R–D* link σ_c^2, with $\sigma_1^2 = 0.01$

noise power on *R–D* link σ_c^2. The network throughput of the ideal relay receiver acts as an upper bound, due to the assumption that the receiver can utilize the same energy for both information processing and energy harvesting. Moreover, JTPS protocol outperforms TSR protocol and PSR protocol in terms of throughput, proving the gain of considering the joint optimization of time and energy partition.

Figure 6a demonstrates the optimal throughput of JTPS under different values of the transmission rate target Ω. It can be observed that network throughput firstly increases with Ω, but then starts to degrade when Ω is above a certain threshold. This can be explained by the fact that for small Ω, the network throughput mainly depends on the rate

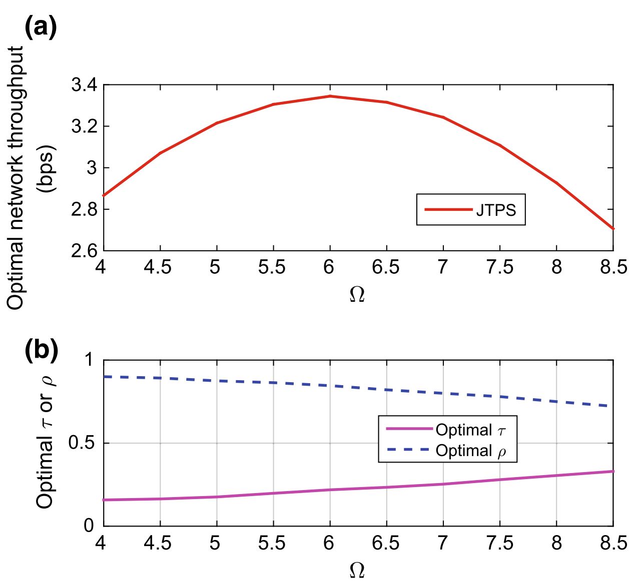

Fig. 6 The optimal network throughput, time switching ratio τ and power splitting ratio ρ versus the transmission rate target Ω

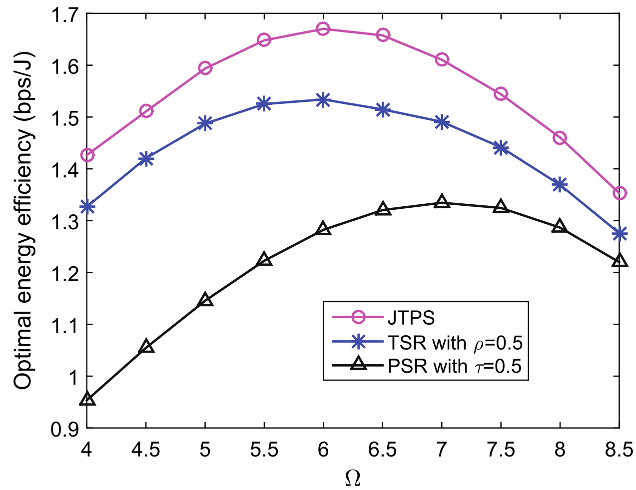

Fig. 7 The optimal energy efficiency versus the transmission rate target Ω

target Ω, therefore, the throughput increases as Ω increases [see (22)]. When Ω is above a certain value, the destination node often fails to decode the signal correctly, resulting in a large outage probability and degrading throughput.

In Fig. 6b, we characterized the optimal values of τ and ρ for the JTPS protocol under different values of the transmission rate target Ω. It can be observed that the optimal value of ρ increases with Ω, while the optimal value of τ decreases when Ω increases. Moreover, the optimal values of τ and ρ jointly maximize the network throughput as shown in Fig. 6a with JTPS protocol.

The energy efficiency of JTPS, TSR and PSR are compared in Fig. 7 with different transmission rate targets Ω. It can be observed that energy efficiency firstly grows as Ω increases, but starts to degrade when Ω is above a certain value. This is due to the fact that the energy efficiency mainly depends on the network throughput [23], since the total energy consumption is constant as the power of destination node holds the same. Furthermore, the JTPS protocol outperforms the TSR and PSR protocols in terms of energy efficiency, which further proves the superiority of our JTPS protocol.

6 Conclusion

In this paper, we propose a JTPS protocol for a relay system powered by energy harvesting, which divides a time slot into two parts. In the first part of the time slot, a portion of the received signal power is used for energy harvesting while the remaining power is used for information processing. In the second part of the time slot, the harvested energy is utilized to transmit signal from relay to destination. The performance metrics including outage probability, network throughput and energy efficiency are deduced in closed form and network throughput is maximized by jointly optimizing the system parameters. Theoretical analysis and simulation results show our JTPS protocol yields superior performance over existing work by jointly considering time and energy partition. It would be interesting to consider the large-scale scenarios with multi-source nodes, multi-relay nodes and full-duplex relays in the future.

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