Optimal Energy Harvesting Scheme for Power Beacon-Assisted Wireless-Powered Networks

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Abstract

In this paper, we consider one-way relay with energy harvesting system based on power beacon (PB), in which the relay node harvests transmitted power from the PB station to forward signals to destination. We also analyse the relay network model with amplify-and-forward (AF) protocol for information cooperation and Power Splitting-based Relaying (PSR) protocol for power transfer. In particular, the outage probability and optimal energy harvesting (EH) power splitting fraction of novel scheme in are presented. We obtain analytical closed-form expression of optimal energy harvesting (EH) power splitting fraction to minimize the outage probability of system. Using numerical and analytical simulations, the performances of different cases are presented and discussed.

Keywords: power beacon, Energy Harvesting, power splitting-based relaying, Amplify and Forward

1.   INTRODUCTION

Recently, wireless access will be a reality in fifth generation (5G) wireless systems, with a series of emerging technology, such as massive multiple-input and multiple-output (MIMO), device-to-device communication and small cell architectures, which have launched a huge data volume in wireless services, such as mobile gaming, mobile TV and mobile Internet. Furthermore, with fast increasing number of users owning smartphones and tablets, and hence one of the most critical problem is that limited operation lifetime of mobile devices due to finite energy ability. To address this hard issue, radio-frequency (RF) based energy harvesting model has received a considerable research interest [1]. A promising technology of RF-assisted energy signals enables wireless energy transfer (WET) to provide continuous and convenient power supply to energy-aware wireless terminals. As a result, wireless powered communication (WPC) system together with wireless devices (WDs) is designed to transfer data to the information receivers (IRs), e.g., sensor nodes. Such terminals is powered up by the means of wireless powered equipment as a dedicated energy transmitters (ETs). In fact, wireless recharging is one of the most desirable new features for mobile devices to eliminate the need of power cords and power chargers. To realize this wireless power transfer, a novel network architecture where stations called power beacons (PBs) are installed in traditional cellular network for boosting operation efficiency of mobiles and sensors via microwave radiation known as microwave power transfer (MPT)

In [2][9], the works have lately adopted some transmission policies for EH cooperative networks. EH relays were first implemented in cooperative communication [2]. In [3][5], assuming a perfect EH model under which the energy arrival time and the amount of harvested energy are calculated prior to transmit such energy, regarding EH relay systems, there were some power allocation policies given. Nevertheless, due to the random energy arrival time and the amount of harvested energy, the deterministic EH model seems to be abstract. Thus, under general energy harvesting profiles, the authors in [6][9] proposed a number of transmission policies. Particularly, there were several joint relay selection and power allocation schemes given due to the stationarity and erodicity of the energy harvesting process [6]. Likewise, in [7], [8], since during any time of data transmission, energy can be scavenged, several power allocation schemes for cooperative EH networks were put forward. The study in [9] based on what have been accomplished in [7]

and [8] to expand the buffer-aided link adaptive EH relay system, in which the change of EH rates can be positively assisted.

In [10], the authors planned the novel impression of deploying dedicated power nodes to enable wireless power transfer in an existing cellular network, named power beacons (PBs). The densities and transmit power of PBs are investigated. By using tool of the stochastic geometry theory under data links' outage constraint. With this PB based energy transfer, we thus could consider a new network , so-called PB-assisted wireless networks. In such networks, each user can harvest wireless energy from the dedicated PB. For this new model, the optimization problem need be solved to optimally allocate the resources of powered network including power and time fraction for wireless power processing and information transmission. To the best of our knowledge, this is still an open question, which motivates this paper. In this paper, we consider a PB relaying network consisting of one PB and relay-destination pair. We assume that the PB are connected to constant power supplies. Each AP (access point) station aims to collect the information from its associated source. It is assumed that each source has no embedded energy supply but has the ability to harvest and store the energy from RF signals broadcast by its AP. The PB is installed to assist APs during the energy harvesting phase. Specifically, we formulate a closed-form expression of the optimal resource power allocation of energy harvesting protocol to obtain optimal outage performance.

The rest of the paper is organized as follows. Section II describes the signal and channel models of the EH enabled relaying network. In Section III, the outage probability and throughput are formulated and solved in order to maximize performance. Numerical results and comparisons are presented in section IV. Finally, summarizing remarks are given in section V.

2. SYSTEM MODEL
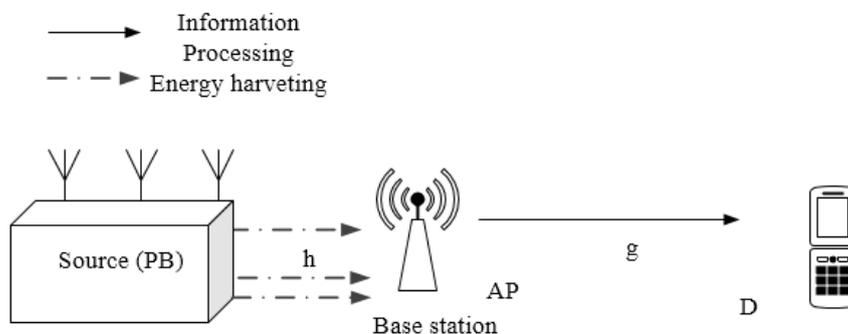
Figure 1. The system model

In this paper, we consider a PB-assisted relaying network consisting of one multi-antenna PB and relay-destination pairs. In view of the state of art and trend of RF energy transfer , the considered network setup is very likely to find its applications in the practical scenario of small cells, such as picocells (range from 10 to 100 meters) and femtocells (WiFi like range), which has been regarded as one of the key enabling technologies of the upcoming 5G cellular networks. It is also worth mentioning that although introducing the PB may result in some extra cost and complexity to the system, this could be beneficial as a whole based on the following considerations:

(i) The PB could be dedicated designed for power transfer only and thus can achieve a higher energy harvesting efficiency by exploiting the benefits of energy beamforming enabled by multiple antennas.

(ii) The PB design is adapted to applications required low power such as in small cell networks.

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(iii) It can be found optimal energy level for energy harvesting phase and calculated at PB. As a result, model of PB can provide wireless charging services in real life.

The entire communication consists of two different phases, namely, energy harvesting and information transmission. Assuming a power fraction of transmitted power of PB during the first phase is assigned to energy transfer, in which the AP station harvest energy from the PB to forward signal to destination D. During the energy harvesting processing stage, the received signal at the AP can be expressed as

$$y_r = \sqrt{P_S}\mathbf{h}_1^T\mathbf{x} + n_r, \tag{1}$$

where n_r is the additive white Gaussian noise (AWGN) with with the variance as N_0.

It is noted that the PB is equipped with multiple antennas, energy beamforming is deployed to progress the performance of energy transfer, i.e.,

$$\mathbf{x} = \mathbf{w}\mathbf{s}, \tag{2}$$

where $\mathbf{w}$ is the beamforming vector with $\mathbf{w} = \mathbf{1}$ and $\mathbf{s}$ is the energy symbol with unit power. Therefore, the optimal beamforming vector is given by

$$\mathbf{w} = \frac{\mathbf{h}^H}{\|\mathbf{h}\|^2}, \tag{3}$$

in which $(.)^H$ denotes the Hermitian transpose matrix.

Following the principle of power splitting -based relay prototcol, the first part in the received RF signal is allocated for energy gathering with power fraction $\rho \in [0,1]$. Applying novel energy harvesting principle, the total expected energy at the end of the first phase at the AP can be calculated as

$$E_h = \eta\rho\left(P_S\|\mathbf{h}\|^2 + N_0\right)T, \tag{4}$$

where $\eta\,(0 < \eta \leq 1)$ is the energy conversion efficiency of the EH circuit, T is block time of signal processing period, P_S is transmit power of the PB. The harvested power at the AP use to forward information to the destination node, e.g. mobile users, this procedure is deployed in the second stage.

Next, the transmitted power at the AP is expressed as

$$P_r = \frac{E_h}{T} = \eta\rho\left(P_S\|\mathbf{h}\|^2 + N_0\right) \tag{5}$$

In practical applications, P_r is greater than 0, which results in $0 < \rho \leq 1$. At the same time of the first stage, the RF signal perform an allocation as $\sqrt{1-\rho}y_r$ for information processing. The received signal in the information processing stage is given by

$$\tilde{y}_r = \sqrt{1-\rho}\left(\sqrt{P_S}hx + n_r\right) + n_p, \tag{6}$$

in which n_p denotes is the additional baseband Gaussian noise with zero mean and variance N_0. In this scenario, the power splitting fraction is selected appropriately for obtaining the optimal outage performance. In this model, AF scheme is applied in relay node, after that the transmitted signal at relay in the second hop is expressed as

$$x_r = \sqrt{P_r}G\left(\rho\right)\tilde{y}_r. \tag{7}$$

In this proposed architecture, the AP is assumed that it equipped by amplify circuit to broaden harvested power and then using such power for the next processing stage. The relay amplifies the received signal and the transmitted signal from the relay by the factor as below

$$G\left(\rho\right) = \sqrt{\frac{1}{(1-\rho)\left(P_S\|\mathbf{h}\|^2 + N_0\right) + N_0}} \tag{8}$$

In the second phase, AP transmits information to mobile user via channel link using the energy harvested in the first phase. Hence, the received signal As a result, received signal at mobile user is formulated by

$$
\begin{aligned}
y_d &= g x_r + n_d \\
&= \sqrt{\frac{(1-\rho)P_S P_r}{(1-\rho)\left(P_S\|\mathbf{h}\|^2 + N_0\right) + N_0}}\,\mathbf{h} g x_S \\
&+ g\sqrt{\frac{P_r}{(1-\rho)\left(P_S\|\mathbf{h}\|^2 + N_0\right) + N_0}}\left(\sqrt{1-p}\,n_r + n_p\right) + n_d
\end{aligned}
\tag{9}
$$

where n_d is additive Gaussian noise with zero mean and variance N_0 and then, the signal-to-noise ratio (SNR) at the end-user can be calculated as.

$$
SNR = \frac{P_S\|\mathbf{h}\|^2 |g|^2}{|g|^2 N_0 + \frac{|g|^2 N_0}{1-\rho} + \frac{N_0}{P_r G(\rho)^2 (1-\rho)}}
\tag{10}
$$

3. OPTIMAL OUTAGE PERFORMANCE

In this section, to address optimal transmission mode, a RTS (requestto-send)/CTS (clear-to-send) scheme is deployed with assumption of faultless channel assessment. Before starting the information transmission, the PB node sends a RTS packet to the the AP node. The AP node analyse received pilot-driven data and can estimate the channel gain h. After receiving the RTS, the AP node returns a CTS packet to the source PB. As a result, the AP node can obtain full CSI, i.e., h before the entire transmission. To obtain the values of g at the PB, we assume to use similar scheme. Similarly, the AP can also estimate g by itself and send feedback to the PB node. It is worth noting that the effect of channel estimation error is out of the scope of our paper. Through the RTS/CTS mechanism, which is compatible with IEEE 802.11 series standards, the AP and PB node can obtain the full CSI before the entire transmission power and data signal. Surely, extra overhead and energy consumption are added to the RTS/CTS processing mechanism in term of channel estimation. But, this hard problem is out of topic of this paper In this investigation, the problem here is that using the knowledge of h and g, we aim to minimize the outage probability which corresponding to maximize the instantaneous SNR at the mobile user.

It is worth noting that the outage event can be expressed as

$$
OP = \Pr\left(SNR < \gamma_0\right),
\tag{11}
$$

in which γ_0 is the threshold SNR.

Therefore, the optimization problem of outage probability can be written as

$$
\begin{aligned}
&\text{maximize} \quad SNR\left(\rho\right) \\
&s.t.\ 0 < \rho < 1
\end{aligned}
\tag{12}
$$

To derive optimal value of power splitting fraction of EH, it is noted that $SNR\left(\rho\right)$ is a nonnegative continuous function ρ . In fact, $SNR\left(\rho\right)$ is a concave function on $0 < \rho < 1$. Here, the first order derivative of $SNR\left(\rho\right)$ with respect to optimal power splitting fraction is derived as result of below equation

$$
\left\{\frac{\partial SNR\left(\rho\right)}{\partial \rho} = 0, 0 < \rho < 1\right\}
\tag{13}
$$

Replacing expression of P_r and G, we obtain new expression of the end-to-end SNR as below

$$
SNR = \frac{P_S\|\mathbf{h}\|^2 |g|^2 \rho\left(1-\rho\right)}{-|g|^2 N_0 \rho^2 + \left(2N_0|g|^2 - N_0\right)\rho + N_0 + \frac{N_0^2}{\|\mathbf{h}\|^2 P_S + N_0}}
\tag{14}
$$

For simplicity, it can be expressed SNR as

$$
SNR = \frac{ax\left(1-\rho\right)}{-b\rho^2 + c\rho + d}
\tag{15}
$$

in which, we denote

$$a = P_S \|\mathbf{h}\|^2 |g|^2, \tag{16}$$

$$b = |g|^2 N_0, \tag{17}$$

$$c = 2N_0 |g|^2 - N_0, \tag{18}$$

$$d = N_0 + N_0^2 / \left(\|\mathbf{h}\|^2 P_S + N_0 \right) \tag{19}$$

It is worth noting that the derivation of SNR is too complicated as below

$$\frac{\partial \left(SNR \right)}{\partial \rho} = \frac{a \left(d - 2d\rho + (b - c)\,\rho^2 \right)}{\left(d + \rho \left(c - b\rho \right) \right)^2} \tag{20}$$

To obtain extreme values, we need to solve the equation $\frac{\partial \gamma(\rho)}{\partial \rho} = 0$. we can see the sign of $\frac{\partial \gamma(\rho)}{\partial \rho}$ corresponds with the numerator term, $f(\rho) = d - 2dx + (b - c)\,x^2$

Hence we just need to solve $f(\rho) = 0$. In this proposed model, ρ^* is found and then it can achieve the maximum SNR

$$\rho* = \begin{cases} \frac{1}{2}, \text{if} b - c = 0 \\ \frac{d - \sqrt{-bd + cd + d^2}}{b - c}, if b - c \neq 0 \end{cases} \tag{21}$$

4. NUMERICAL RESULTS

In this section, the analytical expressions are derived to validate in the previous sections by deploying Monte Carlo simulation results. All the simulation results are acquired by averaging over 10^6 independent experiments. We set the fixed transmission rate $R = 3bps/Hz$, hence the outage SNR threshold is given by $\gamma = 2^R - 1 = 7$. The energy harvesting efficiency is set to be $\eta = 0.9$. Also, we set average channel gain as $\lambda_h = \lambda_g = 1.5$.

We observed that the outage probability achieved by the proposed power splitting policies as shown in Fig. 2. As can be seen clearly, the average outage probability decreases when the transmit power increases. It can be confirmed that the proposed power splitting policies attain better performances than all the other patterns with fixed ρ. That is to say the policy with partial CSI, which incurs less overhead, approaches the policy with full CSI closely. If the RTS/CTS mechanism is not available, policy with partial CSI is suggested

In Fig. 3, it can be freely observed that driving more antennas at the PB can significantly increase the achievable outage probability. This occurrence is quite intuitive, since increasing the number of antennas can provide higher energy beamforming gain, hence, the amount of the harvested energy at the source improves, which in turn reduces the outage probability of the system. This confirms the role of PB in feeding energy to wireless node.

5. CONCLUSION

This paper considered a point-to-point wireless powered communication system, which may find potential applications in future networks such as medical, sensor, and underwater communications systems. A detailed investigation on the average outage performance of such systems was presented with optimal power splitting fraction of nergy harvesting protocol. For power beacon equipped multi antenna for energy transfer transmission modes, the number of antenna contribute to better the average outage performance as seen in numerical result. In addition, a solution of the optimal splitting fraction to minimize the average ouatge was examined, and simulation were obtained, which were shown to be very accurate. Since the optimal split depend on the instantaneous channel state information, it is a low complexity solution to enhance the system performance.
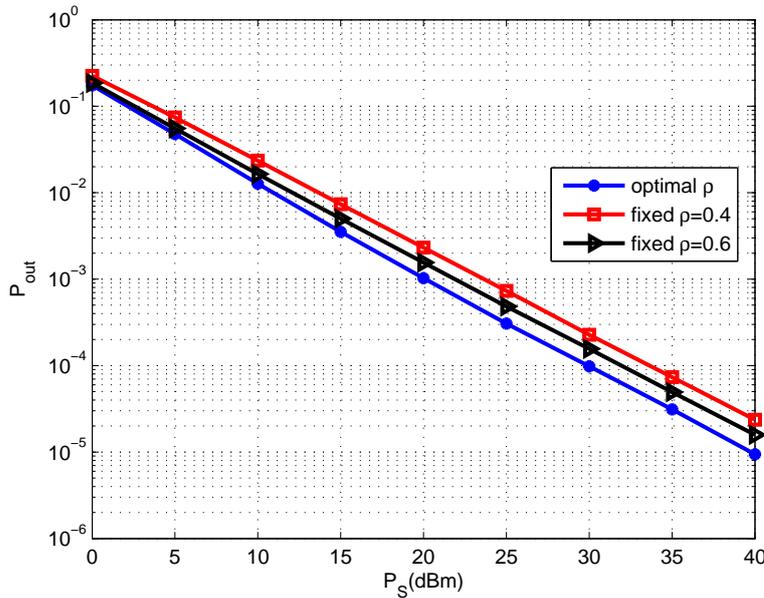
Figure 2. Outage probability at destination node with respect to energy harvesting power splitting fractions ρ
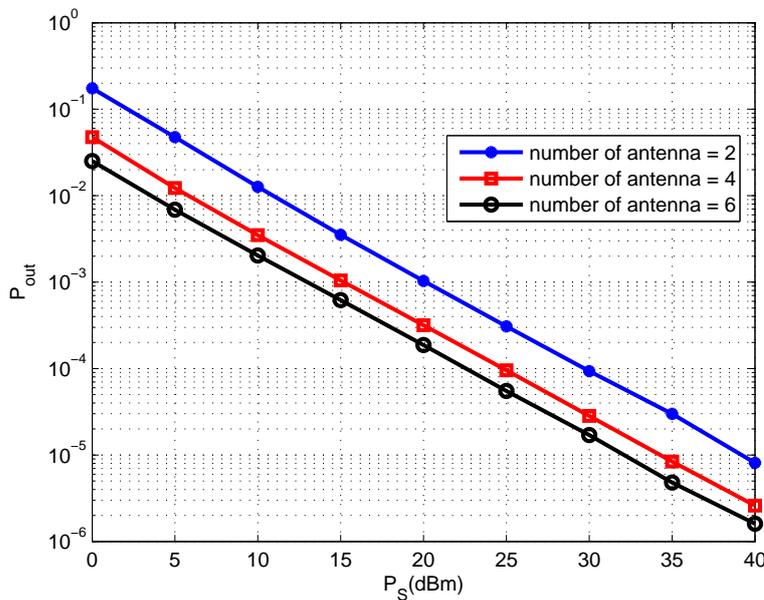
Figure 3. Outage probability destination node with respect to number of antenna at PB

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