# Optimal Power Splitting in a Full-Duplex Wireless Powered Network with a Bidirectional Relay

Yingting Liu[1(✉)], Hongwu Yang[1], Chunman Yan[1], and Li Cong[2]

[1] The College of Physics and Electronic Engineering, Northwest Normal University, No. 967 Anning East Road, Lanzhou, China
{ytliu,yanghw}@nwnu.edu.cn, yancha02@163.com
[2] The Information and Communication Company, Jilin Electric Power Company Limited, Baishan, China
congli8462@163.com

**Abstract.** This paper studies the optimal power splitting strategy in a full-duplex wireless powered communication network (WPCN). This wireless powered network contains three nodes, which are the access point (AP), the relay node (R) and the user. We divide the communication process into two phases that each one has the same duration time. The AP transmits the energy to the relay node and the user, and the user transmits the information to the relay node and the AP simultaneously in the first phase. In the second phase, R relays the energy to the user and simultaneously decodes the information and forwards the information signal to the AP. We study how R splits its harvested energy into two parts separately for energy harvesting (EH) and information forwarding, respectively, to maximize the achievable information rate from the user to the AP, when a direct link between AP and the user exists or does not. We get the mathematical results of optimal power splitting factor in two models. Numerical results show that the variation trend of the maximum achievable rate with the distance between the AP and R, and the rate with direct link is not always larger than the rate without direct link.

**Keywords:** Wireless powered communication network · Energy harvesting Full-duplex · Power splitting · Relay

## 1 Introduction

In conventional wireless networks, concluding sensor networks and cellular networks, wireless devices are usually powered by replaceable or rechargeable batteries, therefore the operation time of these systems are usually limited since the battery power is always limited [1, 2]. In recent years, energy harvesting (EH) becomes an attractive

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approach to take the place of conventional wireless networks since the lifetime of the system using the EH technology is theoretically infinite [1–4]. The communication system which uses energy harvesting technology has the potential to provide a perpetual power supply via harvesting the energy from radiated wireless signal in the surrounding environment [5]. Current wireless power transfer (WPT) technology can effectively transfer tens of microwatts of radio frequency (RF) power to destination node from a distance of more than 10 m [6]. For the above reasons, wireless powered communication networks (WPCNs), in which wireless devices are powered only by WPT, is currently a hot research topic.

The authors developed a noncoherent simultaneous wireless information and power transfer (SWIPT) framework for energy harvesting relay networks, in which relay nodes are operated in decode-and-forward (DF) mode [7] and amplify-and-forward (AF) mode [8], respectively.

In [9], the authors proposed a protocol termed "harvest-then-transmit" for the WPCN, where the hybrid access point (H-AP) first broadcasts wireless energy to all users in the downlink (DL), and then the users transmit their independent information to the H-AP in the uplink (UL) using their individually harvested energy by time-division-multiple-access (TDMA). In [10], the authors studied user cooperation in the WPCN for throughput optimization. In [11], the authors first investigated the bidirectional wireless information and power relaying by the relay node in the WPCN in published papers. The relay node operated in the AF mode simultaneously needs to serve dual roles in the second phase, one is energy relaying in the DL from the AP to the user and another is information relaying in the UL from the user to the AP. They proposed two practical protocols for the considered system based on the power splitting (PS) and time switching (TS) strategies at the relay for maximizing the achievable information rate from the user to the AP. But in [11], the authors have ignored the direct link between the user and the AP both in the information transmission and energy transmission.

In this paper, we consider how the relay node splits harvested energy to maximize the achievable information rate from the user to the AP when the direct link between the user and the AP exists or does not on the basis of [11]. The relay node adopts the decode-and-forward instead of the amplify-and-forward depicted in [11].

## 2 System Model

As shown in Fig. 1, we consider a WPCN in which the user sends information to the AP via a helping relay **R**. It is assumed that both the user and **R** are only powered by energy harvested from the RF signal radiated by the AP. The AP is assumed to have a

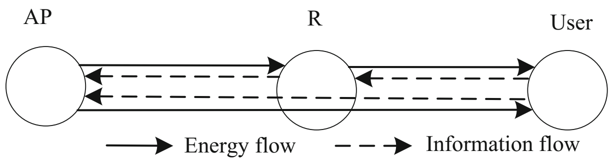
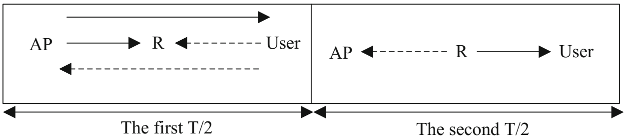
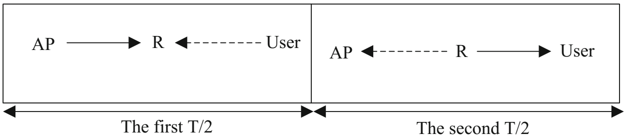



**Fig. 1.** Bidirectional wireless information and power transfer.




(a) Considering the direct link




(b) No direct link

**Fig. 2.** The energy and information transmission process when the direct link exists or does not.

stable energy supply. It is defined that energy flowing direction is the DL and information direction is the UL and are denoted by the solid line and dashed line depicted in Fig. 1, respectively. **R** has the double roles including energy and information relaying in the DL (from the AP to the user) and UL (from the user to the AP), respectively.

The whole transmission is divided into two equal duration phases each denoted by $T/2$ with $T$ denoting the block length. The WPCN is operated in dual-duplex mode when we consider the direct link between the AP and the user. In this mode, the AP sends the RF energy signal to the user and **R** and receives the information signal from the user at the same band in the first phase, and the user receives the energy signal from the AP and sends the information signal to **R** and the AP simultaneously as shown in Fig. 2(a). In the second phase, **R** relays the energy signal to the user and decodes the information then sends it to the AP simultaneously. The AP and the user only receive the information signal and the energy signal, respectively. It is also worth pointing out that the full-duplex concept is simultaneous DL and UL information transmission in the conventional communication system, but in our paper it refers to the simultaneous DL energy transfer and the UL information transmission. Every node equipped with two antennas that one is used for information transfer and another is used for energy transfer, respectively [2].

For full-duplex systems, the self-interference (SI) from the transmitting antenna to the receiving antenna is an important issue. Digital cancellation and analog cancellation can reduce the SI to a negligible level or noise level if the receiving antenna has a good estimate of the transmitted signal [12–15]. So the SI can be easily handled by using existing digital or analog cancellation techniques. For this reason, we assume perfect self-interference cancellation between the two antennas in this paper as in [2, 16].

If ignored the direct link between the AP and the user, the WPCN is operated in half-duplex mode as shown in Fig. 2(b). In the first phase, the AP transmits the energy signal to the user and **R**, the user simultaneously transmits the information signal to **R. R** relays the information and energy signal to the AP and the user using different antenna, and the user and the AP receive the energy and information signal in the second phase, respectively. So in half-duplex mode the user and the AP both have one antenna.

In both modes it is assumed that perfect channel state information (CSI) is available at **R**, our objective is maximize the information rate from the user to the AP by ensuring that the energy consumed at both the user and **R** does not exceed the harvested energy. For simplicity, we assume that the circuit and signal processing power consumption are negligible as compared to the radiation power, which could be the case for energy-efficient wireless devices (such as wireless sensors, tags, etc.) with simple electronics and low signal processing requirement. Furthermore, we assume that both **R** and the user are equipped with a battery with sufficiently large initial energy. Therefore, signal transmission could be initialized before energy harvesting by using the existing energy stored in the battery without violating the energy-causality constraint [11].

# 3 Power Splitting Scheme in Different Situation

In this section, we derive the maximum achievable rate from the user and the AP when the direct link exists or does not.

## 3.1 The Direct Link into Consideration

When a direct link between the user and the AP exists, R uses two directional antennas respectively pointing to the user and the AP, that one is used for the energy and information transmission to the AP and another is used for the energy and information transfer to the user. As described in Sect. 2, the signal received at **R** during the first phase is thus given by

$$\begin{aligned} y_{ra}^{1} &= \sqrt{P_a} h x_a + n_r \quad (a) \\ y_{ru}^{1} &= \sqrt{P_u} g x_u + n_r \quad (b), \end{aligned} \tag{1}$$

where $y_{ra}^{1}$ and $y_{ru}^{1}$ represent the energy signal and the information signal received by **R** at each antenna, which are send by the AP and the user, respectively. $P_a$ and $P_u$ denote the transmit power of the AP and the user, respectively. $h$ and $g$ represent the channel gain coefficients from the AP and the user to **R**, respectively. We assume channel reciprocity so that the DL and UL have the identical channel gain. It is assumed that both the DL and UL channels are quasi-static flat-fading, where channel coefficients remain constant during each block transmission. $n_r$ denotes the additive white Gaussian noise received at **R**; $x_a$ and $x_u$ denote the energy and information signals sent by the AP and the user, respectively. We assume that $x_a$ is a unit-power deterministic signal that is known to **R** and the user, whereas $x_u$ is a random signal following zero-mean unit-variance circularly symmetric complex Gaussian (CSCG) distribution, denoted as $x_u \sim CN(0,\ 1)$.

The signals received by the user and the AP in the first phase are given by the Eqs. (2) and (3).

$$y_u^1 = \sqrt{P_a} l x_a + n_u \tag{2}$$

$$y_{AP}^1 = \sqrt{P_u} l x_u + n_{AP} \tag{3}$$

$l$ denotes the channel coefficient from the AP and the user. $n_u$ and $n_{AP}$ denote additive white Gaussian noise received at the user and the AP, respectively. $P_u$ is connected with the sum of harvested energy in the first phase from the AP and in the second phase from **R,** which expression is shown in the Eq. (9).

Considering $P_u \ll P_a$ in practice, **R** only harvests energy from $y_{ra}^1$, so the average energy harvested at **R** during each block is then given by

$$E_r = \eta \mathrm{E}[|y_{ra}|^2](T/2) = \eta P_a |h|^2 (T/2) \tag{4}$$

where $E[.]$ denotes the statistical expectation, and $0 < \eta \leq 1$ denotes the energy conversion efficiency for the energy harvesting circuit at **R** and the user. The received energy signal given in (1.a) at **R** is split into two parts: one for energy relaying to the user, and the other for information relaying to the AP, both in the second phase. In the second phase, **R** simultaneously relays energy signal $x_a$ to the user using the energy $\rho E_r$ and information signal $x_u$ to the AP using the residual energy $(1-\rho)E_r$ with different directional antennas, where $\rho$ is the power splitting ratio factor for energy harvesting and its value is between 0 and 1. Considering the fact that **R** adopts the decode-and-forward mode and assuming that the bit error rate is zero, we obtain the received signal at the AP in the second phase is shown as

$$y_{AP}^2 = \sqrt{\eta(1-\rho)P_a} |h|^2 x_u + n_{AP} \tag{5}$$

and the received signal at the user is shown as

$$y_u^2 = \sqrt{\eta \rho P_a} h g x_a + n_u \tag{6}$$

Since the energy harvested by the user is equal to the sum of the energy harvested from the AP and **R**, combining the Eqs. (2) and (4), we can obtain the energy harvested by the user in the whole transmission block which is shown as

$$E_u = \eta\left(\eta \rho P_a |h|^2 |g|^2 + P_a |l|^2\right) T/2 \tag{7}$$

So the power $P_u$ of the user is shown as

$$P_u = \sqrt{\eta\left(\eta \rho P_a |h|^2 |g|^2 + P_a |l|^2\right)} \tag{8}$$

Combining the equations from (1) to (8), the achievable rate among nodes in the whole block transmission are shown as

$$R_{U-AP} = 1/2\log\left(1 + \frac{\eta\left(\eta\rho P_a|h|^2|g|^2 + P_a|l|^2\right)|l|^2}{\sigma_{AP}^2}\right) \tag{9}$$

$$R_{R-AP} = 1/2\log\left(1 + \frac{\eta(1-\rho)P_a|h|^4}{\sigma_{AP}^2}\right) \tag{10}$$

$$R_{U-R} = 1/2\log\left(1 + \frac{\eta\left(\eta\rho P_a|h|^2|g|^2 + P_a|l|^2\right)|g|^2}{\sigma_r^2}\right) \tag{11}$$

$R_{U-AP}$ denotes the information rate from the user to the AP through the direct link in the first phase, and $R_{U-R}$ is the information rate from the user to **R** in the first phase, respectively. $R_{R-AP}$ is the information rate from **R** to the AP through the relaying link in the second phase, and the achievable information rate $R'$ form the user to the AP in a transmission block time denoted by $T$ is expressed by [10]

$$R' = \min(R_{U-AP} + R_{R-AP}, R_{U-R}) \tag{12}$$

Considering the value domain of $\rho$, the problem of maximizing the information rate from the user to the AP in a block time can be formulated as

$$R = \max\ \min(R_{U-AP} + R_{R-AP}, R_{U-R}), 0 \le \rho \le 1 \tag{13}$$

It is assumed that the received noise powers of all nodes are equal to $\sigma^2$ for simplicity of analysis. Considering the nature of the logarithmic function, we can get the following equation with some simple manipulations

$$f(\rho) = -a\rho^2 + b\rho + c, 0 \le \rho \le 1 \tag{14}$$

In Eq. (14),

$$a = \eta^3 P_a^2|h|^6|g|^2 \tag{15}$$

$$\begin{aligned} b = &\left(\eta^2|h|^2|g|^2\sigma^2 - \eta|h|^4 - \eta^2|h|^4|g|^4\right)P_a \\ &+ \left(\eta^3|h|^6|g|^2 - \eta^2|h|^4|l|^4\right)P_a^2 \end{aligned} \tag{16}$$

and

$$c = \sigma^4 - \sigma^2 + \left(\eta|h|^4\sigma^2 + \eta|l|^4\sigma^2 - \eta|l|^2|g|^2\right)P_a + \eta^2|h|^4|l|^4P_a^2 \tag{17}$$

Now the problem of maximizing the achievable rate described in (13) is converted into finding the extreme value of the function (14). According to the nature of the parabolic function and the range of $\rho$, we can finally get the value of $\rho$ meeting the requirement of the Eq. (13). Because calculating the value of the power splitting factor is a little tedious, we can get the maximum achievable rate through computer simulation using the method of exhausting searching.

### 3.2 Without the Direct Link

In this case, due to space limit, we omit the derivation process and give the results directly using the same analysis process which is depicted as part 1. The achievable rate from the user to the AP is shown as

$$R_{NO} = 1/2\log(1 + \frac{(1-\rho)\eta P_a h^4}{\sigma^2}) \tag{18}$$

Observing the Eq. (18), it is obviously that the maximum achievable rate is obtained when $\rho$ is equal to zero. This means that the achievable rate is maximized if **R** utilizes the whole harvested energy for relaying information signal. This is not possible in practice. It is explained that the bit error and outage probability when transmitting the information signal between nodes are both ignored in the paper [11]. So **R** can receive the information signal complete correctly even if the transmission power of the user is equal to zero. Obviously, the achievable rate from the user to the AP is maximizing when **R** relay the information signal to the AP utilizing the whole harvested energy, since **R** is closer to the AP than the user and the corresponding channel power attenuation is lower than the user. The results presented in this paper can be used as performance ceiling for similar systems.

## 4 Numerical Results

The parameters selected in this paper are the same as in [16]. The distance between the user and the AP is set to 10 m. **R** is located in the line connecting the AP and the user. $\eta$ is equal to 0.8. For each user, the DL and UL channel power gains are modeled as $|h|^2 = 10^{-3}\theta d_{ar}^{-\alpha}$, $|g|^2 = 10^{-3}\theta d_{ur}^{-\alpha}$, and $|l|^2 = 10^{-3}\theta d_{au}^{-\alpha}|$, respectively, in which $\theta$ represents the channel short-term fading in the DL and UL and is independent exponential random variables with unit mean. $d_{ar}$, $d_{ur}$ and $d_{au}$ denote the distance between the AP and **R**, between the user and **R,** and between the AP and the user, respectively. In the above channel model, a 30 dB average signal power attenuation is assumed at a reference distance of 1 m. It is assumed the received noise power spectral density of all nodes is −160 dBm/Hz and the bandwidth is set as 1 MHz. $P_a$ is set to 20 dBm.

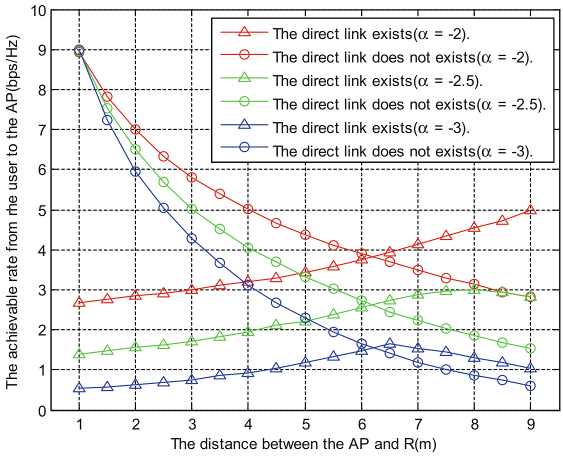



**Fig. 3.** The maximum achievable information rates when the direct link exists or not.

Figure 3 shows the maximum achievable information rates between the user and the AP when the direct link exists or does not. It is observed an interesting phenomenon that the maximum achievable information rates with the direct link are significantly less than when there is no direct path, when the distance between the AP and **R** is less than 6 m. This is in contradiction to our intuition. In fact, when a direct link exists, the user is far away from the AP, so the power attenuation is very large via the direct link. If **R** is closer to the AP, the relaying power is lower because the power experiences a greater attenuation from **R** to the user, although harvested energy by **R** is larger in this case. Considering the above reasons, the received energy of the user is very low when the distance between the AP and **R** is short. But the achievable rate from the user to AP is shown in the Eq. (13), the transmission power of the user directly limits the achievable rate at this time. When we ignore the direct link, because we neglect both the outage probability and the bit error rate at this time, **R** can utilize the whole harvested energy to relay the information signal. When **R** is closer to AP, the power attenuation is lower and accordingly the achievable rate is larger. This is why the maximum achievable rate with the direct link existing is lower than the rate ignored the direct link when **R** is closer to the AP than the user. The achievable rate with the direct link is larger than with the direct link not existing when **R** is closer to the user, and **R** helps the user to increases the achievable rate to the AP at this time.

The achievable rate monotonic decreases along with the increase of the distance between the AP and **R** when the direct link does not exist as shown in Fig. 3, no matter what the value of $\alpha$ is, and the achievable rate decreases more quickly as $\alpha$ is lower. Obviously, the achievable rate when $\alpha$ is larger is always larger than when $\alpha$ is lower no matter whether the direct link exists or not.

With the increase of the distance between the AP and **R**, the achievable rate monotonically increases when $\alpha$ is equal to $-2$, and first monotonically increases and then monotonically decreases when $\alpha$ is equal to the other values. When **R** is closer to the user, the relaying information signal power experiences a larger attenuation.

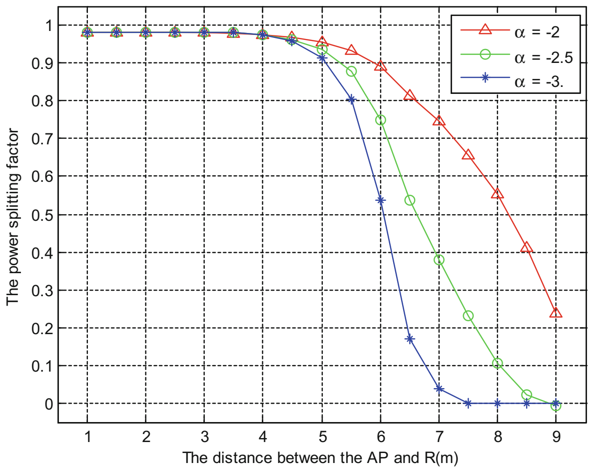



**Fig. 4.** The different values of the power splitting factor with the different values of α.

Although the whole harvested energy by **R** ($\rho = 0$) is used to forward the information signal at this time, it is still difficult to change the trend of the rate of decline and the influence of power attenuation plays a major role in this situation, as shown in Figs. 3 and 4. The power splitting factor when **R** is closer to the user decreases more quickly, and the trend is more obvious when $\alpha$ is lower.

## 5 Conclusions

In this paper, we study a WPCN system with a bidirectional information/energy forwarding relay operated in the decode-and-forward mode when the direct link exists or not. The corresponding achievable rate maximization problems are formulated and optimally solved ignoring the outrage probability. Numerical results show that the relay node can only help the user increases the achievable rate to the AP when the relay node is closer to the user when the direct link exists. The results presented in this paper can be used as performance ceiling for similar systems.

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