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Energy Efficiency Analysis of Bidirectional Wireless Information and Power Transfer for Cooperative Sensor Networks

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ABSTRACT In this paper, we study the energy efficiency of bidirectional wireless information and power transfer in cooperative sensor networks, where the relay node can decode and forward information from the sensor node (SN) to base station (BS), and assist the wireless power transfer from the BS to SN. For the power splitting protocol, we propose the joint power allocation scheme to maximize the energy efficiency. For the time switching protocol, the optimal power allocation strategy and the optimal time allocation scheme are derived by studying the derivative of the energy efficiency. Simulation results are provided to verify the performance of our proposed schemes for the cooperative sensor networks.

INDEX TERMS Energy efficiency, wireless power transfer, decode-and-forward, power splitting, time switching.

I. INTRODUCTION

As a new green technique, energy harvesting can enable the wireless device to obtain the energy from natural or man-made source [1]–[4]. Based on the energy source (e.g., solar, wind and radio frequency signal), there exist many kinds of energy harvesting techniques [5]–[8]. In particular, the radio frequency energy harvesting technique, which is commonly called wireless power transfer, has recently received much research attention due to the stability and availability of the wireless signal [9]–[13].

Note that the radio frequency signal can simultaneously carry the energy and information. Then, to achieve simultaneous wireless information and power transfer, Zhang and Ho [14] proposed the power splitting (PS) and time switching (TS) protocols. The throughput-energy trade-offs of PS protocol and TS protocol were investigated in [15] and [16], respectively. For wireless sensor and cooperative networks, the sensor node (SN) and relay node (RN), which need the external power supply, can harvest energy by wireless power transfer. Therefore, Krikidis *et al.* [17] and Ding *et al.* [18] analyzed the wireless-powered cooperative systems, which can employ the TS or PS half-duplex based relay protocols to complete information transmission. The throughput of amplify-and-forward (AF) based and decode-and-forward (DF) based wireless-powered cooperative systems were studied in [19] and [20], respectively. For both AF and DF relay protocols, Liu [21] investigated the throughput maximization problem of wireless-powered cooperative multi-relay systems. When a group of SNs need to cooperate for both information and energy transfers, bidirectional wireless information and power transfer was proposed for the cooperative sensor networks [22], where the RN can transfer wireless power from the base station (BS) to the SN, and also amplify and forward information from the SN to BS. To further increase the throughput, the DF relay protocol based bidirectional wireless information and power transfer was proposed for cooperative multi-relay networks [23], where multiple RNs can transfer wireless power from the BS to SN, and also decode and forward information from the SN to BS by distributed space-time coding. Moreover, for the bidirectional wireless information and power transfer with energy accumulating relay, Hou *et al.* [24] proposed

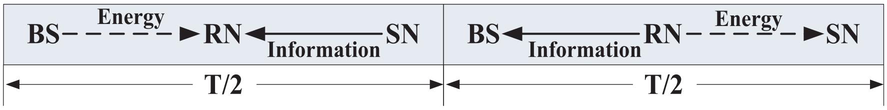

FIGURE 1. Power splitting protocol for cooperative sensor networks.

the continuous-time and discrete-time energy harvesting protocols. Due to the increasing global energy consumption and environmental protection consciousness, much research attention has been paid to energy efficiency, which will be an important metric for wireless communications [25]–[30]. However, to the best of the authors' knowledge, there is little work about the energy efficiency analysis of bidirectional wireless information and power transfer.

In this paper, we investigate the energy efficiency of bidirectional wireless information and power transfer in cooperative sensor networks, where the RN can assist the wireless power transfer from the BS to SN, and decode and forward information from the SN to BS. To maximize the energy efficiency, the joint power allocation scheme is proposed for PS protocol. Furthermore, for the TS protocol, we obtain the optimal time allocation scheme and power allocation strategy by analyzing the derivative of the energy efficiency.

The rest of the paper is organized as follows. We describe the system model in Section II. For the cooperative sensor networks with PS protocol, the joint power allocation scheme is proposed to maximize the energy efficiency in Section III. For TS protocol, by studying the derivative of the energy efficiency, Section IV gives the optimal time allocation and power allocation schemes. Simulation experiments are conducted to verify the effectiveness of the proposed resource allocation strategies in Section V. Finally, we conclude the paper in Section VI.

II. SYSTEM MODEL

This paper considers the system model, which is composed of the BS, RN and SN. Note that the RN is the sensor that can act as relay. Due to deep fading, there is no direct link between the BS and SN. RN can help the wireless power transfer from the BS to SN and the information transmission from the SN to BS. Half-duplex protocol and DF relay protocol are employed in this paper. Both RN and SN have the rechargeable storage unit, which is a battery to support the switching between wireless power and information transfers [17], [18], [31]–[33]. Moreover, by using the existing energy in SN battery, the information transmission can be initialized before energy harvesting. In one frame duration T, RN and SN consume the energy harvested from the BS [19]–[21].

We denote the channel coefficients from the BS and SN to RN by h and g, respectively. They are both reciprocal and follow the stationary block fading model. h and g vary independently across different frame durations, but remain constant in one frame duration. RN has the perfect channel state information (CSI). The energy efficiency of the PS protocol and TS protocol will be analyzed in cooperative sensor networks.

III. POWER SPLITTING PROTOCOL

For PS protocol, the entire transmission process includes two stages. The frame duration of each stage is $T/2$. As depicted in Fig.1, RN harvests energy from the BS by wireless power transfer and SN transmits signal to RN for information transmission in the first stage. Thus, the RN received signal r_r is

$$r_r = \sqrt{P_s} x_s g + \sqrt{P_b} x_b h + z_r, \tag{1}$$

where P_s and P_b denote the transmitted powers of the SN and BS, respectively; z_r is the additive Gaussian noise received by RN; $x_s \sim \mathcal{CN}(0, 1)$[1] and x_b denote the information signal transmitted by the SN and the energy signal transmitted by BS, respectively. Moreover, RN knows the unit-power deterministic signal x_b.

The PS factor is ρ $(0 \leq \rho \leq 1)$. Then, RN assigns ρ portion of the received signal r_r in Eq.(1) to power its battery. During the second stage, the remaining $1-\rho$ portion of r_r is used for energy and information relay. In one frame duration, the harvested energy of RN can be written as

$$E_r = \xi\rho\mathbb{E}\{|r_r|^2\}(T/2) \approx \xi\rho P_b |h|^2 (T/2), \tag{2}$$

where $\mathbb{E}\{\cdot\}$ is the expectation operation; $0 < \xi \leq 1$ represents the energy conversion efficiency; $|h|^2$ denotes the channel gain from BS to RN. Compared with P_b, the noise is small [22], [23]. The harvested energy of SN is originated from BS via RN. This results in $P_s \ll P_b$, which can be explained by Eq.(6). Therefore, the energy harvested from the SN and noise can be ignored. In the second stage, the transmitted power of RN can be expressed as

$$P_r = \xi\rho P_b |h|^2. \tag{3}$$

Then, we can write the remaining signal at RN as

$$r_r^1 = \sqrt{1-\rho}\big(\sqrt{P_s} x_s g + \sqrt{P_b} x_b h + z_r\big). \tag{4}$$

As in [22] and [23], with perfect knowledge of h and x_b, RN can remove the energy signal x_b from r_r^1. Then, the signal in Eq.(4) becomes $r_r^2 = \sqrt{1-\rho}\big(\sqrt{P_s} x_s g + z_r\big) + z_r'$, where $z_r' \sim \mathcal{CN}(0, \sigma_r^2)$ represents the additional processing noise at RN, which dominates the Gaussian noise z_r. Consequently, z_r can be ignored. The received signal-to-noise ratio (SNR) of RN can be denoted by $\eta_r = (1-\rho)P_s|g|^2/\sigma_r^2$, where $|g|^2$ is the channel gain from SN to RN.

[1] $\mathcal{CN}(\mu, \sigma^2)$ represents the circularly complex symmetric Gaussian distributed random variable with mean μ and variance σ^2.

In the second stage, RN simultaneously transfers energy and information to SN and BS, respectively. The received signal of BS can be denoted by $r_b = \sqrt{P_r} x_s h + z_b$, where $z_b \sim \mathcal{CN}(0, \sigma_b^2)$ is the additive Gaussian noise received by BS. The received SNR of BS can be written as $\eta_b = P_r|h|^2/\sigma_b^2$. Therefore, the SNR of cooperative sensor networks can be expressed as

$$\eta = \min\{\eta_r, \eta_b\} = \min\{(1-\rho)P_s|g|^2/\sigma_r^2, P_r|h|^2/\sigma_b^2\}. \quad (5)$$

The SN received signal is denoted by $r_s = \sqrt{P_r} x_s g + z_s$, where $z_s \sim \mathcal{CN}(0, \sigma_s^2)$ is the additive Gaussian noise received by SN. The energy harvested from the noise is small and thus ignored. The harvested energy of SN can be written as $E_s = \xi \mathbb{E}\{|r_s|^2\}(T/2) \approx \xi^2 \rho P_b |h|^2|g|^2(T/2)$. Therefore, the SN transmitted power is

$$P_s = P_b(\rho\xi^2|h|^2|g|^2). \quad (6)$$

Note that P_s is proportional to P_b and the coefficient $\rho\xi^2|h|^2|g|^2$ is much less than one. The assumption of $P_s \ll P_b$ is reasonable, which verifies Eq.(2). By substituting Eq.(3) and Eq.(6) into η, we get the following expression:

$$\eta = P_b m(\rho) = P_b \cdot \min\{m_1(\rho), m_2(\rho)\}, \quad (7)$$

where $m_1(\rho) = (\rho - \rho^2)\xi^2|h|^2|g|^4/\sigma_r^2$ and $m_2(\rho) = \rho\xi|h|^4/\sigma_b^2$. Thus, the network throughput is $I_P = \frac{1}{2}\log_2(1 + P_b m(\rho))$.

Then, the following problem is formulated to maximize the energy efficiency [28], [29], which is an important metric for the cooperative sensor networks.

$$\boldsymbol{P1}: \max_{P_b,\rho} \zeta_p(P_b, \rho) = \frac{\log_2(1 + P_b m(\rho))}{\alpha P_b + 2P_c} \quad (8a)$$
$$\text{s.t.}: \ 1).\ 0 < P_b \le P_{\max}; \quad (8b)$$
$$2).\ 0 \le \rho \le 1, \quad (8c)$$

where α denotes the reciprocal of power amplifier efficiency; P_c and $P_{\max}$ are the circuit power consumption and the maximum transmitted power, respectively. Note that when $m(\rho)$ obtains the maximum value, the energy efficiency gets the maximum value. Furthermore, P_b has no impact on $m(\rho)$. Instead of solving problem $\boldsymbol{P1}$ directly, we can decompose the problem $\boldsymbol{P1}$ into two subproblems.

The first subproblem, denoted by $\boldsymbol{P1a}$, can be given as follows:

$$\boldsymbol{P1a}: \max_{\rho} m(\rho) = \min\{m_1(\rho), m_2(\rho)\} \quad (9a)$$
$$\text{s.t.}: \ 1).\ 0 \le \rho \le 1. \quad (9b)$$

Note that $m_1(\rho) = (\rho - \rho^2)\xi^2|h|^2|g|^4/\sigma_r^2$ is a concave function and gets the maximum value for $\rho = 1/2$. When ρ is equal to 0 and 1, $m_1(\rho)$ will equal 0. $m_2(\rho) = \rho\xi|h|^4/\sigma_b^2$ is a monotone increasing function of ρ. For $\rho = 0$, $m_2(\rho)$ is equal to 0.

The objective function of $\boldsymbol{P1a}$ in Eq.(9) is determined by the minimum value between $m_1(\rho)$ and $m_2(\rho)$. When $m_1(\rho)$ equals $m_2(\rho)$, we can obtain two solutions: 0 and $\rho_1 = 1 - (|h|^2\sigma_r^2)/(\xi|g|^4\sigma_b^2)$. Note that $\rho_1 \in (-\infty, 1]$. We can analyze problem $\boldsymbol{P1a}$ by two conditions: (i)$\rho_1 \le 1/2$ and (ii)$1/2 < \rho_1 \le 1$.

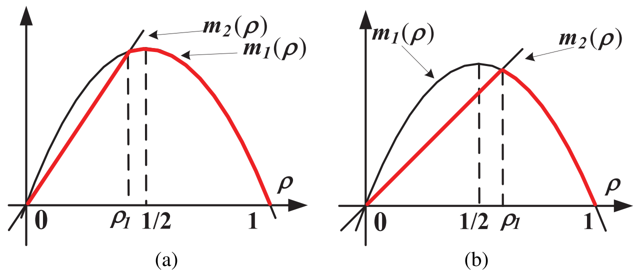

FIGURE 2. Graphical representations for the two conditions, where the red curves represent $m(\rho)$. (a) $\rho_1 \le 1/2$. (b) $1/2 < \rho_1 \le 1$.

For condition (i), $m(\rho)$ increases monotonically with ρ in $[0, 1/2]$, and then $m(\rho)$ is a monotone decreasing function of ρ in $[1/2, 1]$. Problem $\boldsymbol{P1a}$ reaches the maximum value when ρ is equal to $1/2$, which can be shown in Fig.2(a). For condition (ii), we can see that $m(\rho)$ is a monotone increasing function of ρ in $[0, \rho_1]$, and then $m(\rho)$ decreases monotonically with ρ in $[\rho_1, 1]$. For $\rho = \rho_1$, problem $\boldsymbol{P1a}$ obtains the maximum value, which is depicted in Fig.2(b). Therefore, the optimal PS factor of problem $\boldsymbol{P1a}$ is

$$\rho_* = \max\{1/2, \rho_1\}. \quad (10)$$

Furthermore, the maximum value of $m(\rho)$ can be expressed as follows:

$$m_* = (\rho_* - \rho_*^2)\xi^2|h|^2|g|^4/\sigma_r^2. \quad (11)$$

Based on Eq.(11), we can formulate the second subproblem $\boldsymbol{P1b}$ as follows:

$$\boldsymbol{P1b}: \max_{P_b} \zeta_p(P_b) = \frac{\log_2(1 + P_b m_*)}{\alpha P_b + 2P_c} \quad (12a)$$
$$\text{s.t.}: \ 1).\ 0 < P_b \le P_{\max}. \quad (12b)$$

The derivative of $\zeta_p(P_b)$ with respect to P_b can be written as

$$\frac{\partial \zeta_p(P_b)}{\partial P_b} = \frac{\frac{m_*(\alpha P_b + 2P_c)}{\ln 2(1+P_b m_*)} - \alpha \log_2(1 + P_b m_*)}{(\alpha P_b + 2P_c)^2}. \quad (13)$$

In Eq.(13), $(\alpha P_b + 2P_c)^2$ is greater than zero. For the sake of simplification, the numerator of Eq.(13) can be defined as follows:

$$N_1(P_b) = \frac{m_*(\alpha P_b + 2P_c)}{\ln 2(1 + P_b m_*)} - \alpha \log_2(1 + P_b m_*). \quad (14)$$

Obviously, the sign of Eq.(14) determines the sign of Eq.(13). Taking the derivative of $N_1(P_b)$ with respect to P_b, we can have

$$\frac{\partial N_1(P_b)}{\partial P_b} = -\frac{m_*^2(\alpha P_b + 2P_c)}{\ln 2(1 + P_b m_*)^2}. \quad (15)$$

Note that $\partial N_1(P_b)/\partial P_b < 0$ in $(0, P_{\max}]$ and $N_1(0) > 0$. If there exists the value $P_b^0 \in (0, P_{\max}]$ that makes $N_1(P_b^0) = 0$ hold, $\zeta_p(P_b)$ is a monotone increasing function of

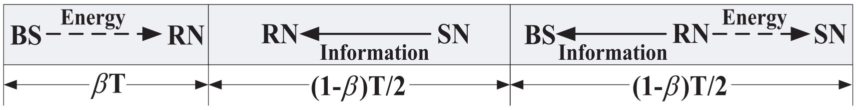

FIGURE 3. Time switching protocol for cooperative sensor networks.

Algorithm 1 Joint Power Allocation Scheme

1) Initialization with $P_1 = 0$, $P_2 = P_{\max}$ and maximum tolerance $\epsilon > 0$;
2) Calculate ρ_*, m_* and $\varphi = \frac{\partial \zeta_p(P_b)}{\partial P_b}|_{P_b=P_{\max}}$ based on Eqs.(10), (11) and (13);
3) **If** $\varphi < 0$ **then**
4) **While** $|P_2 - P_1| \geq \epsilon$ **do**
5) Calculate $\psi = \frac{\partial \zeta_p(P_b)}{\partial P_b}|_{P_b=\frac{P_1+P_2}{2}}$ based on Eq.(13);
6) **If** $\psi \geq 0$ **then**
7) Set $P_1 = \frac{P_1+P_2}{2}$;
8) **Else**
9) Set $P_2 = \frac{P_1+P_2}{2}$;
10) **End if**
11) **End while**
12) **Else**
13) Set $P_1 = P_{\max}$;
14) **End if**
15) $\rho = \rho_*$ and $P_b = P_1$ are the optimal solutions.

P_b in the region $(0, P_b^0]$, and then $\zeta_p(P_b)$ decreases monotonically with P_b in $[P_b^0, P_{\max}]$. The optimal solution is $P_b^* = P_b^0$. Otherwise, since $\zeta_p(P_b)$ is a monotone increasing function of P_b in $(0, P_{\max}]$, the optimal solution is $P_b^* = P_{\max}$. Thus, for PS protocol, we propose the joint power allocation scheme to obtain the optimal solution of problem $\boldsymbol{P1}$.

IV. TIME SWITCHING PROTOCOL

The energy efficiency of cooperative sensor networks with TS protocol is studied in this section. The entire transmission process consists of three stages, which is depicted in Fig.3. β denotes the TS factor. During the first stage, the BS will transfer power to RN. Similarly to the cooperative sensor networks with PS protocol, the harvested energy of RN can be written as $E_r = \xi P_b|h|^2(\beta T)$. Therefore, during the third stage, the RN transmitted power is

$$P_r = 2\xi P_b|h|^2\beta/(1-\beta). \tag{16}$$

In the second stage, the SN transmits information signal to RN. The received SNR at RN can be denoted by $\eta_r = P_s|g|^2/\sigma_r^2$. During the third stage, RN transfers energy and information to SN and BS, respectively. The received SNR at the BS is $\eta_b = P_r|h|^2/\sigma_b^2$. Furthermore, the harvested energy of SN is $E_s \approx \xi P_r|g|^2(1-\beta)T/2$. Therefore, in the second stage, the transmitted power of SN is denoted by

$$P_s = 2\xi^2 P_b|h|^2|g|^2\beta/(1-\beta). \tag{17}$$

The network throughput is $I_T = \frac{1-\beta}{2}\log_2(1+\min\{\eta_r, \eta_b\})$. Since the sensor is energy-constrained, it is necessary to maximize the energy efficiency of cooperative sensor networks. The optimization problem can be expressed as follows:

$$\boldsymbol{P2}: \max_{P_b,\beta} \zeta_t(P_b,\beta) = \frac{(1-\beta)\log_2\left(1+\frac{P_b\beta w}{1-\beta}\right)}{2(\alpha\beta P_b + P_c)} \tag{18a}$$

$$\text{s.t.}: 1).\ 0 < P_b \leq P_{\max}; \tag{18b}$$

$$2).\ 0 \leq \beta \leq 1, \tag{18c}$$

where $w = \min\{2\xi^2|h|^2|g|^4/\sigma_r^2, 2\xi|h|^4/\sigma_b^2\}$. If the objective function of Eq.(18) is concave in the two-dimensional space (P_b, β), the optimal joint time and power allocation scheme can be obtained. The Hessian matrix of $\zeta_t(P_b,\beta)$ can be derived as

$$\mathrm{T} = \begin{bmatrix} t_{11} & t_{12} \\ t_{21} & t_{22} \end{bmatrix} = \begin{bmatrix} \frac{\partial^2 \zeta_t(P_b,\beta)}{\partial P_b^2} & \frac{\partial^2 \zeta_t(P_b,\beta)}{\partial P_b \partial \beta} \\ \frac{\partial^2 \zeta_t(P_b,\beta)}{\partial \beta \partial P_b} & \frac{\partial^2 \zeta_t(P_b,\beta)}{\partial \beta^2} \end{bmatrix}. \tag{19}$$

If $t_{11} < 0$ and $t_{11}t_{22} - t_{12}t_{21} > 0$, $\zeta_t(P_b,\beta)$ in Eq.(18) will be concave [34]. We can derive t_{11} as

$$t_{11} = \frac{(1-\beta)N_2}{2\ln 2\left(1+\frac{P_b\beta w}{1-\beta}\right)^2(\alpha\beta P_b + P_c)^3}, \tag{20}$$

where N_2 can be written as Eq.(21), which is shown on the bottom of the next page.

In Eq.(20), $(1-\beta)$ and $2\ln 2\left(1+\frac{P_b\beta w}{1-\beta}\right)^2(\alpha\beta P_b + P_c)^3$ are both greater than zero, the sign of t_{11} can be determined by the sign of N_2. The first derivative and second derivative of N_2 with respect to P_b can be derived as

$$\frac{\partial N_2}{\partial P_b} = 4\alpha^2\beta^2\frac{\beta w}{1-\beta}\left(1+\frac{P_b\beta w}{1-\beta}\right)\ln 2\log_2\left(1+\frac{P_b\beta w}{1-\beta}\right) - 4\alpha\beta\left(\frac{\beta w}{1-\beta}\right)^2(\alpha\beta P_b + P_c) \tag{22}$$

and

$$\frac{\partial^2 N_2}{\partial P_b^2} = 4\alpha^2\beta^2\left(\frac{\beta w}{1-\beta}\right)^2\ln 2\log_2\left(1+\frac{P_b\beta w}{1-\beta}\right). \tag{23}$$

Note that $\partial^2 N_2/\partial P_b^2 > 0$. Moreover, based on $\partial N_2/\partial P_b$ and $\partial^2 N_2/\partial P_b^2$, we can come to a conclusion that N_2 is greater than zero for relatively large transmitted power, which is denoted by P_l. Correspondingly, t_{11} is greater than zero when P_b is greater than P_l. Thus, when the transmitted power is relatively large, problem $\boldsymbol{P2}$ is not concave. The closed-form expression of exact P_l can not be obtained. Moreover, the expression of $t_{11}t_{22} - t_{12}t_{21}$ is extremely complicated to determine the sign, which means that it is difficult to judge whether $\boldsymbol{P2}$ is concave. The optimal joint time and power allocation scheme is hard to obtain based on the above analysis. Consequently, we investigate the optimal power allocation strategy and the optimal time allocation scheme, respectively.

A. OPTIMAL POWER ALLOCATION STRATEGY

The optimal power allocation strategy will be given to maximize the energy efficiency in this subsection. We can formulate the optimization problem as follows:

$$\boldsymbol{P3}: \max_{P_b} \zeta_t(P_b) = \frac{(1-\beta)\log_2\left(1+\frac{P_b\beta w}{1-\beta}\right)}{2(\alpha\beta P_b + P_c)} \quad (24a)$$
$$\text{s.t.}: \ 1).\ 0 < P_b \leq P_{\max}. \quad (24b)$$

Then, the first derivative of $\zeta_t(P_b)$ can be derived as

$$\frac{\partial \zeta_t(P_b)}{\partial P_b} = \frac{1-\beta}{2}\frac{\frac{\beta w(\alpha\beta P_b+P_c)}{\ln 2(1-\beta+P_b\beta w)} - \alpha\beta\log_2\left(1+\frac{P_b\beta w}{1-\beta}\right)}{(\alpha\beta P_b+P_c)^2}. \quad (25)$$

In Eq.(25), $2(\alpha\beta P_b + P_c)^2$ is greater than zero. The sign of Eq.(25) only depends on its numerator, which can be expressed as follows:

$$N_3(P_b) = (1-\beta)\left[\frac{\beta w(\alpha\beta P_b+P_c)}{\ln 2(1-\beta+P_b\beta w)} - \alpha\beta\log_2\left(1+\frac{P_b\beta w}{1-\beta}\right)\right] \quad (26)$$

The derivative of $N_3(P_b)$ with respect to P_b can be derived as

$$\frac{\partial N_3(P_b)}{\partial P_b} = -\frac{(1-\beta)(\beta w)^2(\alpha\beta P_b+P_c)}{\ln 2(1-\beta+P_b\beta w)^2}. \quad (27)$$

In $(0, P_{\max}]$, $\partial N_3(P_b)/\partial P_b$ is less than zero. Thus, $N_3(P_b)$ is a monotone decreasing function of P_b in $(0, P_{\max}]$. Note that $N_3(0) > 0$. If there does not exist the value $P_b^0 \in (0, P_{\max}]$ that makes $N_3(P_b^0) = 0$ hold, $P_{\max}$ is the optimal solution. This is due to the fact that $\zeta_t(P_b)$ is a monotone increasing function of P_b in $(0, P_{\max}]$. Otherwise, P_b^0 is the optimal solution. This is because $\zeta_t(P_b)$ increases monotonically with P_b in $(0, P_b^0]$, and then $\zeta_t(P_b)$ is a monotone decreasing function of P_b in $[P_b^0, P_{\max}]$. Thus, we propose the power allocation strategy to obtain the optimal transmitted power P_b^*.

B. OPTIMAL TIME ALLOCATION SCHEME

To maximize the energy efficiency, the time allocation scheme is proposed in this subsection. We can formulate the optimization problem as

Algorithm 2 Power Allocation Strategy

1) Initialization with $P_1 = 0$, $P_2 = P_{\max}$ and maximum tolerance $\epsilon > 0$;
2) Calculate $\varphi = \frac{\partial \zeta_t(P_b)}{\partial P_b}|_{P_b=P_{\max}}$ based on Eq.(25);
3) **If** $\varphi < 0$ **then**
4) **While** $|P_2 - P_1| \geq \epsilon$ **do**
5) Calculate $\psi = \frac{\partial \zeta_t(P_b)}{\partial P_b}|_{P_b=\frac{P_1+P_2}{2}}$ based on Eq.(25);
6) **If** $\psi \geq 0$ **then**
7) Set $P_1 = \frac{P_1+P_2}{2}$;
8) **Else**
9) Set $P_2 = \frac{P_1+P_2}{2}$;
10) **End if**
11) **End while**
12) **Else**
13) Set $P_1 = P_{\max}$;
14) **End if**
15) $P_b = P_1$ is the optimal solution.

$$\boldsymbol{P3}: \max_{\beta} \zeta_t(\beta) = \frac{(1-\beta)\log_2\left(1+\frac{P_b\beta w}{1-\beta}\right)}{2(\alpha\beta P_b + P_c)} \quad (28a)$$
$$\text{s.t.}: \ 1).\ 0 \leq \beta \leq 1. \quad (28b)$$

The first derivative of $\zeta_t(\beta)$ with respect to β can be written as

$$\frac{\partial \zeta_t(\beta)}{\partial \beta} = \frac{\frac{P_b w(\alpha\beta P_b+P_c)}{\ln 2(1-\beta+P_b\beta w)} - (\alpha P_b + P_c)\log_2\left(1+\frac{P_b\beta w}{1-\beta}\right)}{2(\alpha\beta P_b+P_c)^2}. \quad (29)$$

In Eq.(29), $2(\alpha\beta P_b + P_c)^2$ is greater than zero. Thus, we can determine the sign of Eq.(29) by the numerator, which can be written as

$$N_4(\beta) = \frac{P_b w(\alpha\beta P_b+P_c)}{\ln 2(1-\beta+P_b\beta w)} - (\alpha P_b + P_c)\log_2\left(1+\frac{P_b\beta w}{1-\beta}\right). \quad (30)$$

The derivative of $N_4(\beta)$ with respect to β can be given as follows:

$$\frac{\partial N_4(\beta)}{\partial \beta} = \frac{-P_b^2 w^2(\alpha\beta P_b+P_c)}{\ln 2(1-\beta)(1-\beta+P_b\beta w)^2}. \quad (31)$$

Clearly, in the region $[0, 1]$, $\partial N_4(\beta)/\partial\beta$ is less than zero. Thus, $N_4(\beta)$ is a monotone decreasing function of β in the region $[0, 1]$. Note that $N_4(0) > 0$ and $N_4(1) < 0$. Thus, there exists the value $\beta^0 \in [0, 1]$, which satisfies $N_4(\beta^0) = 0$. $\zeta_t(\beta)$ is a monotone increasing function of β in $[0, \beta^0]$, and then $\zeta_t(\beta)$ decreases monotonically with β in $[\beta^0, 1]$.

$$N_2 = 2\alpha^2\beta^2\left(1+\frac{P_b\beta w}{1-\beta}\right)^2 \ln 2\log_2\left(1+\frac{P_b\beta w}{1-\beta}\right) - \frac{\beta w}{1-\beta}\left[\frac{\beta w}{1-\beta}(\alpha\beta P_b+P_c) + 2\alpha\beta\left(1+\frac{P_b\beta w}{1-\beta}\right)\right](\alpha\beta P_b+P_c) \quad (21)$$

Algorithm 3 Time Allocation Scheme

1) Initialization with $\beta_1 = 0$, $\beta_2 = 1$ and maximum tolerance $\epsilon > 0$;
2) **While** $|\beta_2 - \beta_1| \geq \epsilon$ **do**
3) Calculate $\psi = \frac{\partial \zeta_t(\beta)}{\partial \beta} |_{\beta = \frac{\beta_1+\beta_2}{2}}$ based on Eq.(29);
4) **If** $\psi \geq 0$ **then**
5) Set $\beta_1 = \frac{\beta_1+\beta_2}{2}$;
6) **Else**
7) Set $\beta_2 = \frac{\beta_1+\beta_2}{2}$;
8) **End if**
9) **End while**
10) $\beta = \beta_1$ is the optimal solution.

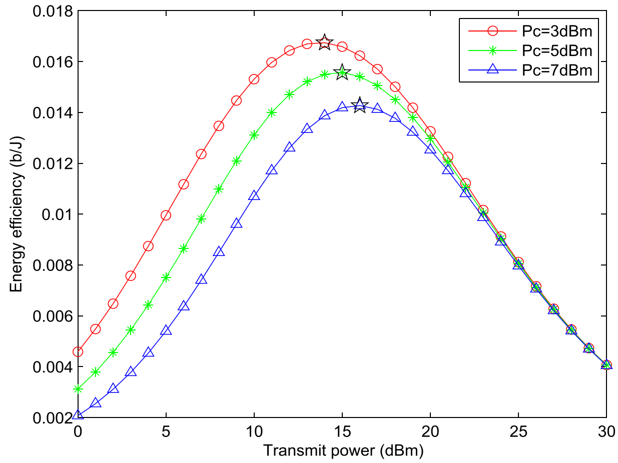

FIGURE 4. The energy efficiency of cooperative sensor networks with PS protocol.

β^0 is the optimal solution β^*. Therefore, we propose the time allocation scheme to obtain the optimal time switching factor.

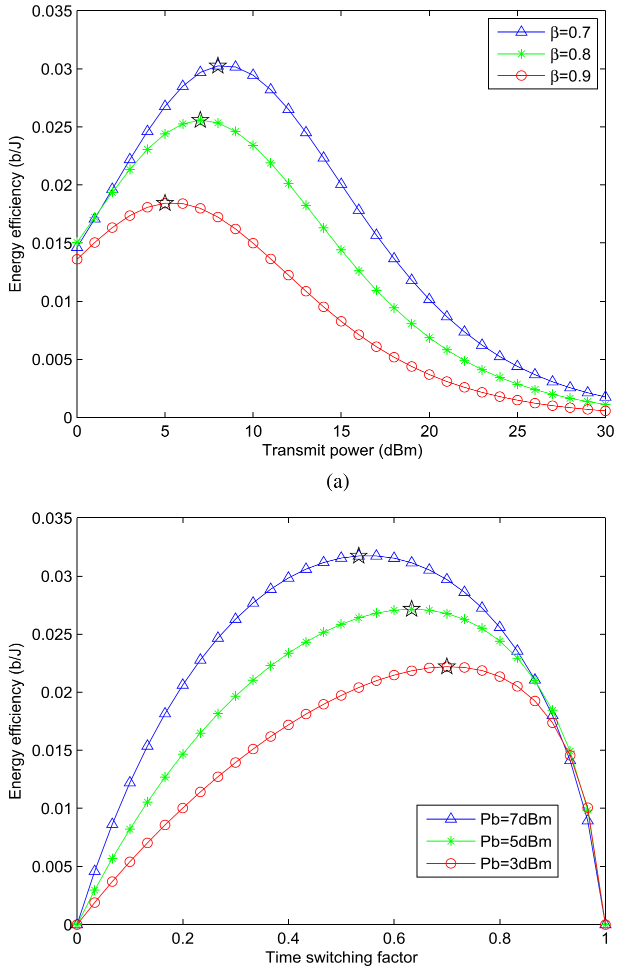

FIGURE 5. The performance of power allocation strategy and time allocation scheme for cooperative sensor networks with TS protocol. (a) The energy efficiency under various transmitted power. (b) The energy efficiency versus the time-switching factor.

V. SIMULATION RESULTS

In this section, we provide the simulation results to verify the effectiveness of the proposed schemes for cooperative sensor networks. Throughout simulations, the reciprocal of the power amplifier efficiency and the energy conversion efficiency are $\alpha = 1$ and $\xi = 0.1$, respectively. We set the maximum transmitted power as $P_{\max} = 30$dBm and the noise power as $\sigma_r^2 = \sigma_b^2 = -50$ dBm, respectively. The channel coefficients g and h are both set to be $c \cdot L^{-\gamma}$, where c follows Rayleigh fading, $L = 5$ m represents the transmitter-receiver distance and $\gamma = 2$ denotes the path loss exponent.

Figure 4 evaluates the performance of joint power allocation scheme for the cooperative sensor networks with PS protocol. We set the circuit power consumption P_c as 3dBm, 5dBm and 7dBm, respectively. The pentagram notation is the point of maximum energy efficiency. As described in Fig.4, the energy efficiency is a monotone increasing function of the transmitted power P_b in $(0, P_b^*]$, and then energy efficiency decreases monotonically with the transmitted power P_b in $[P_b^*, P_{\max}]$.

In Fig.5(a), we plot the energy efficiency under various transmitted power P_b. The time-switching factors are 0.7, 0.8 and 0.9, respectively. Furthermore, we set the circuit power consumption P_c as 5dBm. The pentagram notations of these three curves correspond to the maximum energy efficiency with different optimal transmitted power P_b^*. We can find that the energy efficiency increases and decreases monotonically as the transmitted power increases in the regions $(0, P_b^*]$ and $[P_b^*, P_{\max}]$, respectively.

Figure 5(b) depicts the energy efficiency versus the time-switching factor. The circuit power consumption is $P_c = 5$dBm. Moreover, the transmitted powers are 3dBm, 5dBm and 7dBm, respectively. The pentagram notation denotes the maximum energy efficiency corresponding to optimal time-switching factor β^*. We can see that the energy efficiency increases monotonically with the time-switching factor in $[0, \beta^*]$, and then the energy efficiency is a monotone decreasing function of the time-switching factor in the range of $[\beta^*, 1]$.

VI. CONCLUSIONS

For cooperative sensor networks, this paper studied the energy efficiency of bidirectional wireless information and power transfer, which can achieve the wireless information transmission from the SN to BS and the wireless power transfer from the BS to SN. To maximize the energy efficiency, we obtained the joint power allocation scheme for PS protocol. Then, by investigating the derivative of energy efficiency, the optimal power allocation scheme and optimal time allocation strategy were derived for TS protocol. Simulation experiments were conducted to verify the effectiveness of our proposed schemes.

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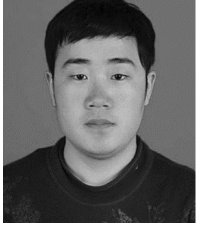

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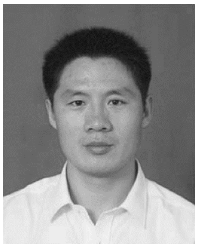

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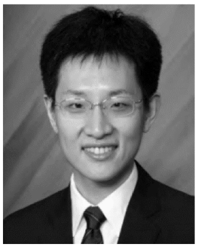

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