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Energy-Spectral Efficiency in Simultaneous Wireless Information and Power Transfer

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Abstract—**In this paper, energy efficiency (EE) and spectral efficiency (SE) in simultaneous wireless information and power transfer (SWIPT) systems are studied. First, unlike the concepts of EE and SE in conventional wireless communications, we propose four new definitions of EE and SE for SWIPT systems by taking account of two different applications of SWIPT. They are EE for information transfer, EE for energy harvesting, SE for information transfer, and SE for energy harvesting. Then, the transmit power and switching factor are selected as two key parameters influencing EE and SE in SWIPT. Finally, different EE-SE trade-off and optimization strategies are proposed for various working conditions. Numerical results verify that the proposed optimal system performance can be achieved by setting appropriate system parameters.**

***Index terms*— SWIPT, energy harvesting, energy efficiency, spectral efficiency, energy-spectral efficiency trade-off.**

I. INTRODUCTION

Energy harvesting is a reliable approach to prolong the lifetime of energy constrained wireless networks. Two types of implementation methods for wireless power transfer (WPT) can be used, which are electro-magnetic induction [1] and radio-frequency (RF) signals. The RF signals allow for a longer transmission distance compared to the electro-magnetic induction for WPT. In addition, RF signals have been widely applied in wireless information transmission (WIT). SWIPT via RF signals is suitable for wireless sensor network (WSN) and offers great convenience to mobile users [2].

The idea of transmitting information and power simultaneously has been proposed for the first time by Varshney in [3]. The concept of SWIPT was further improved and developed in [4] and [5]. The fundamental methods to coordinate WIT and WPT at the receiver side can be divided into three categories, time switching (TS), power splitting (PS), and spectral splitting (SS). For the TS, the received block is divided into two parts, that is, one period for energy harvesting (EH) and the other period for information transfer (IT) [6]. The principle of PS is splitting the signal power into two streams for EH and IT dynamically or statically [5]. Similarly, the SS uses a dedicated bandwidth for EH and the left bandwidth for IT. For each of the three methods, there will always be a variable which illustrates the splitting ratio of the RF signal for information transfer and energy harvesting. The splitting factor and transmit power can be identified as the two most important parameters for a SWIPT system [7].

The concern about the scarcity of spectral resources is increasing with the increasing requirements for wireless applications and devices. Much attention has been paid to the importance of SE. In addition, improving the EE plays an important role in a communication system [8] in terms of prolonging the lifetime of energy constrained wireless networks as well as saving transmit power. The necessity for optimizing SE and EE in the wireless communication system has been widely discussed in [9]. Although lots of efforts have been made in the area of EE and SE trade-offs, the optimization of EE and SE in SWIPT system is still missing. There will be a broad application prospect in the future for the SWIPT and there are significant potential for the optimization of EE and SE in a SWIPT system [7]. Thus, the EE and SE and the corresponding EE-SE trade-off in SWIPT should be studied. The trade-off of rate and energy has been discussed in [2], but there are no precise definitions of EE and SE in SWIPT to the best of our knowledge.

In this paper, we mainly investigate the relationship between EE and SE in SWIPT by proposing the new definitions of EE for IT, EE for EH, SE for IT, and SE for EH, and design a new strategy for optimizing the system settings (transmit power and splitting factor) in order to achieve the optimal trade-offs between EE and SE.

The remainder of this paper is organized as follows. Section II describes the system model. The definitions of EE for IT, EE for EH, SE for IT, SE for EH, and universal strategy for adjusting the system settings are introduced in Section III. Section IV provides simulation results and analyses. Finally, conclusions are given in Section V.

II. SYSTEM MODEL

A. SWIPT

In this paper, the single-input single-output (SISO) system is applied and the TS method is employed to achieve SWIPT in order to simplify the calculation. The TS SISO SWIPT system is illustrated in Fig. 1. A complete transmit block is divided into two parts for the receiver, where T is a whole symbol duration, αT is the time for EH and $(1-\alpha)T$ is the time for IT. In addition, there is a power source at the transmitter. A battery or super capacitor is placed at the receiver so as to prolong the lifetime of the wireless networks [13].

B. Channel model

It is assumed that the SISO channel from the transmitter to the receiver is a quasi-static flat-fading channel. Based on the above system settings, the data rate and harvested power with transmit power $P_{\rm t}$ and switching factor α in the SWIPT system can be expressed as follows:

$$R(\alpha, P_{\rm t}) = (1-\alpha)Blog_2(1+\frac{P_{\rm t}h\theta}{BN_0}) \tag{1}$$

$$P_e(\alpha, P_{\rm t}) = \alpha\xi P_{\rm t}h\theta \tag{2}$$

where α is the TS factor, $P_{\rm t}$ is the transmit power, B is the bandwidth, θ denotes the signal power attenuation, N_0 is the noise spectral density, h is the quasi-static channel fading and ξ is the RF to DC convert efficiency in the receiver side. The EE and SE for SWIPT can be calculated using (1) and (2). In the conventional RF wireless communication systems, the transmit power $P_{\rm t}$ is one of the most important parameters that influencing the trade-off between EE and SE [15]. But for a SWIPT system, a switching mechanism is added to the system to achieve SWIPT. Taking the EH approach into consideration, it is necessary to propose a new conception of EE and SE for EH. Based on (1) and (2), the transmit power $P_{\rm t}$ and the switching factor α should be chosen as the two key variables influencing the optimization on EE and SE in SWIPT.

III. EE AND SE IN SWIPT

The definitions of EE and SE in conventional wireless communications have been widely discussed in [15]. As for the SWIPT, the new definitions of EE and SE should be established for the RF signals consumed for EH. In this section, EE and SE have been given the specific definitions for IT and EH scenarios.

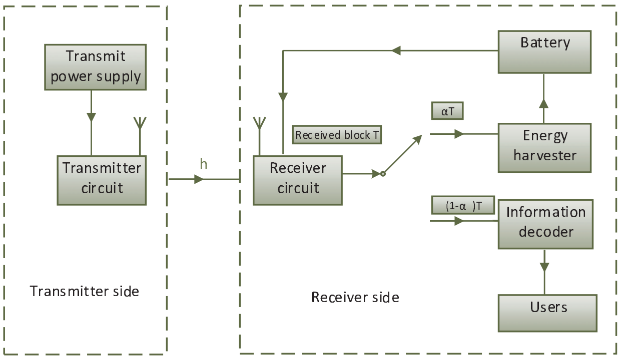

Fig. 1: System structure for a SWIPT system.

A. EE and SE for IT

The SE for IT can be expressed as

$$\eta_{\rm SEIT} = \frac{R}{B} = \frac{(1-\alpha)Blog_2(1+\frac{P_{\rm t}h\theta}{BN_0})}{B}. \tag{3}$$

The EE for IT can be expressed as

$$\eta_{\rm EEIT} = \frac{R}{P_{\rm t}+P_{\rm c}} = \frac{(1-\alpha)Blog_2(1+\frac{P_{\rm t}h\theta}{BN_0})}{P_{\rm t}+P_{\rm c}}. \tag{4}$$

It can be derived from (3) that $\eta_{\rm SEIT}$ always increases with the growth of transmit power $P_{\rm t}$. There is a linear negative correlation between switching factor α and $\eta_{\rm SEIT}$. When it refers to EE for IT, (4) shows that $\eta_{\rm EEIT}$ has a fast decline with the increase of transmit power $P_{\rm t}$ under the same switching factor α, where $P_{\rm c}$ is the circuit power consumption for information transfer. The system cannot get a high $\eta_{\rm SEIT}$ and $\eta_{\rm EEIT}$ at the same time, which is similar to the conventional wireless communication systems. There is also a trade-off between $\eta_{\rm SEIT}$ and $\eta_{\rm EEIT}$ which has been widely discussed in the traditional RF communication field [9]. In conventional RF communication, we usually use economic efficiency to optimize the balance between $\eta_{\rm SEIT}$ and $\eta_{\rm EEIT}$ [10]. But in a SWIPT system, there are two factors influencing the trade-off of $\eta_{\rm SEIT}$ and $\eta_{\rm EEIT}$, $P_{\rm t}$ and switching factor α , we can optimize EE and SE subject to $P_{\rm t}$ and α [11], and this problem will be discussed in Section IV.

B. EE and SE for EH

The EE for EH can be expressed as

$$\eta_{\rm EEEH} = \frac{P_{\rm e}}{P_{\rm t}+P_{\rm c}} = \frac{\alpha\xi P_{\rm t}h\theta}{P_{\rm t}+P_{\rm c}}. \tag{5}$$

The SE for EH can be expresses as

$$\eta_{\rm SEEH} = \frac{P_{\rm e}}{B} = \frac{\alpha\xi P_{\rm t}h\theta}{B}. \tag{6}$$

From (5), the $\eta_{\rm EEEH}$ is directly proportional to the switching factor α and has a positive relationship with transmit power $P_{\rm t}$. With the increase of $P_{\rm t}$,the $\eta_{\rm EEEH}$ will get closer but never reach an upper bound $\eta_{\rm EEEH,max} = \alpha\xi h\theta$ due to the existence of circuit power $P_{\rm c}$. Also, as described in (6), the SE for EH $\eta_{\rm SEEH}$ has a positive correlation with α and $P_{\rm t}$ and will reach the culmination when $P_{\rm t} = P_{\rm t,max}$ and $\alpha = 1$.

A SWIPT system may be used in various application scenarios [6], and the SWIPT system might be set up for common WSN or special communication function in special position. But there are common constraints in all applications, such as available bandwidth, transmit power supply and battery capacity. In a SWIPT system, robustness of the system is the most important thing. Thus there must be a lower bound of R and $P_{\rm t}$ to make sure that the system works perfectly. Thus, we can set R_0 and $P_{\rm e0}$ to specific values according to different performance requirements, i.e.,

$$P_{\rm e}(\alpha, P_{\rm t}) = \alpha\xi P_{\rm t}h\theta \geq P_{\rm e0} \tag{7}$$

$$R(\alpha, P_{\rm t}) = (1-\alpha)Blog_2(1+\frac{P_{\rm t}h\theta}{BN_0}) \geq R_0. \tag{8}$$

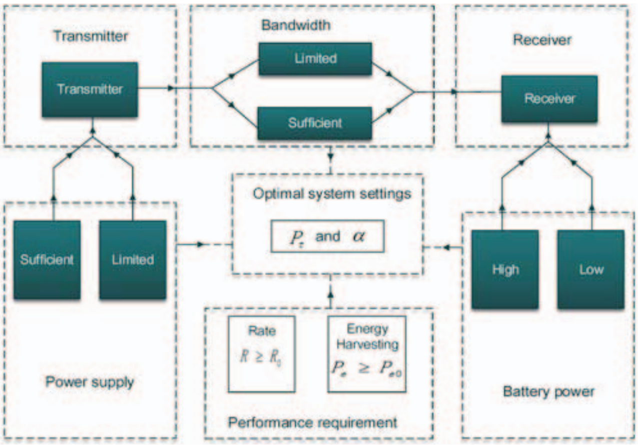

Fig. 2: Syetem settings adjustment flow diagram for a SWIPT system.

By combining (7) and (8), the switching factor α can be derived as

$$\frac{P_{\mathrm{e}0}}{\xi P_{\mathrm{t}} h\theta} \leq \alpha \leq 1 - \frac{R_0}{Blog_2(1+\frac{P_{\mathrm{t}} h\theta}{BN_0})}. \tag{9}$$

Setting α to the maximum and minimum according to (9), we can get the minimum value of P_{t} with the constraint condition of $P_{\mathrm{e}0}$ referring to (7) and get another minimum value of transmit power P_{t} with the constraint condition of R_0 referring to (8). Thus the expression of the transmit power P_{t} can be expressed as (10)

$$P_{\mathrm{t,min}} = max[\frac{BN_0(2^{R_0}-1)}{h\theta}, \frac{P_{\mathrm{e}0}}{h\theta\xi}] \leq P_{\mathrm{t}} \leq P_{\mathrm{t,max}} \tag{10}$$

where $P_{\mathrm{t,max}}$ is the available maximum value of P_{t} and $P_{\mathrm{t,min}}$ is the available minimum value of P_{t}. It is shown in Fig. 2, there are a power supply for the transmitter and a battery providing power for the receiver, the system transmit information and power using a constant bandwidth. Three types of resources have influence on the optimization of EE and SE for a SWIPT system, which are the transmit power supply, available bandwidth and battery power. Each of the resources has two states, sufficient or limited. Then the working condition for a SWIPT system can be divided into eight different cases against the three resources. A critical value $\kappa_{\mathrm{B}0}$ is proposed, which is set to 20 mAh, when κ_{B} is larger than $\kappa_{\mathrm{B}0}$, the system is turned into information priority mode, otherwise the system is turned into energy priority mode. Different optimizing strategies are designed to get the optimal trade-off result between η_{EEIT}, η_{SEIT}, η_{EEEH}, and η_{SEEH}, and the optimal system settings of α and P_{t} will be calculated under a specific system parameters. Then we will discuss the optimizations of η_{EEIT}, η_{SEIT}, η_{EEEH}, and η_{SEEH} under different working conditions.

C. Optimizations under sufficient P_t supply and plenty of B

Under this situation, we assume that there are abundant transmit power supply and plenty of bandwidth resources accommodated for the SWIPT system. Therefore there is no need to consider the value of EE or SE and we can just aim at getting a higher rate or harvested power.

1) Battery power is abundant:

When $\kappa_{\mathrm{B}} \geq \kappa_{\mathrm{B}0}$, the system is turned into information priority mode, and optimizing the system performance is equivalent to maximizing rate of the system in order to get the best working performance. The optimal value of α and P_{t} can be expressed as (11).

$$\begin{aligned} &[\alpha, P_{\mathrm{t}}] = \arg\max\left\{(1-\alpha)\, Blog_2\left(1+\frac{P_{\mathrm{t}} h\theta}{BN_0}\right)\right\}, \\ &\text{s.t.}\quad \alpha \in [0,1], P_t \in [P_{\mathrm{t,min}}, P_{\mathrm{t,max}}]. \end{aligned} \tag{11}$$

2) Battery power is insufficient:

When $\kappa_{\mathrm{B}} \leq \kappa_{\mathrm{B}0}$, the system is turned into energy priority mode, optimizing the system performance is equivalent to maximizing harvested energy of the system in order to get the best working performance. The optimal value of α and P_{t} can be expressed as (12)

$$\begin{aligned} &[\alpha, P_{\mathrm{t}}] = \arg\max\left\{\alpha\xi P_{\mathrm{t}} h\theta\right\}, \\ &\text{s.t.}\quad \alpha \in [0,1], P_t \in [P_{\mathrm{t,min}}, P_{\mathrm{t,max}}]. \end{aligned} \tag{12}$$

D. Optimizations under sufficient P_t supply and limited B

Under this situation, we assume that there are abundant transmit power supply and limited bandwidth resources accommodated for the SWIPT system. So there is no need to consider the value of the EE. We can just aim at maximizing the SE for IT or EH.

1) Battery power is abundant:

When $\kappa_{\mathrm{B}} \geq \kappa_{\mathrm{B}0}$, the system is turned into information priority mode, optimizing the system performance is equivalent to maximizing η_{SEIT}. According to the analyses mentioned above, $\eta_{\mathrm{SEIT}}(\alpha, P_{\mathrm{t}})$ has the same increase-decrease trends as (11) against α and P_{t}, thus we can optimize the system settings by (11).

2) Battery power is insufficient:

When $\kappa_{\mathrm{B}} \leq \kappa_{\mathrm{B}0}$, the system is turned into energy priority mode, optimizing the system performance is equivalent to maximizing η_{SEEH} of the system. For a constant bandwidth B, maximizing η_{SEEH} is the same as maximizing harvested power P_{t}, hence the optimal value of α and P_{t} can be derived from (12).

E. Optimizations under limited P_t supply and plently of B

Under this situation, we assume that there are limited transmit power supply and plenty of bandwidth resources accommodated for the SWIPT system. There is no need to consider the value of the SE. The goal for EE-SE trade-offs is getting a higher EE for IT or EH.

1) Battery power is abundant:

When $\kappa_{\mathrm{B}} \geq \kappa_{\mathrm{B}0}$, the system is turned into information priority mode, optimizing the system performance is equivalent to maximizing η_{EEIT}. The optimal value of α and P_{t} can be expressed as

$$[\alpha, P_{\text{t}}] = \arg\max \left\{ \frac{(1-\alpha)Blog_2(1+\frac{P_{\text{t}}h\theta}{BN_0})}{P_{\text{c}}+P_{\text{t}}} \right\}, \qquad (13)$$
$$\text{s.t.} \quad \alpha \in [0,1], P_t \in [P_{\text{t,min}}, P_{\text{t,max}}].$$

For any value of P_{t}, the partial derivative of η_{EEIT} against α can be calculated, $\frac{\partial \eta_{\text{EEIT}}}{\partial \alpha} \leq 0$. In order to get the maximum of η_{EEIT}, we set α to the lower bounder of α. Here lies the optimal expression of switching factor $\alpha(P_{\text{t}})$

$$\alpha = \frac{P_{\text{e0}}}{\xi P_{\text{t}} h \theta}. \qquad (14)$$

Substituting (14) into (13), we can get the formula to solve the optimal value of α and P_{t} as follows:

$$[\alpha, P_{\text{t}}] = \arg\max \left\{ \frac{(1-\frac{P_{\text{e0}}}{\xi P_{\text{t}} h\theta})Blog_2(1+\frac{P_{\text{t}}h\theta}{BN_0})}{P_{\text{c}}+P_{\text{t}}} \right\}, \qquad (15)$$
$$\text{s.t.} \quad \alpha \in [0,1], P_t \in [P_{\text{t,min}}, P_{\text{t,max}}].$$

2) Battery power is insufficient:

When $\kappa_{\text{B}} \leq \kappa_{\text{B0}}$, the system is turned into energy priority mode, optimizing the system performance is equivalent to maximizing η_{EEEH}. The optimal value of α and P_{t} can be expressed as (16)

$$[\alpha, P_{\text{t}}] = \arg\max \left\{ \frac{\alpha \xi P_{\text{t}} h\theta}{P_{\text{c}}+P_{\text{t}}} \right\} \qquad (16)$$
$$\text{s.t.} \quad \alpha \in [0,1], P_t \in [P_{\text{t,min}}, P_{\text{t,max}}].$$

F. Optimizations under limited P_t supply and limited B

Under this situation, we assume that there are limited transmit power supply and limited bandwidth resources accommodated for the SWIPT system, thus it is of great importance to improve η_{EEIT}, η_{SEIT}, η_{EEEH}, and η_{SEEH}. The trade-offs among η_{EEIT}, η_{SEIT}, η_{EEEH}, and η_{SEEH} are discussed as follows.

1) Battery power is abundant:

When $\kappa_{\text{B}} \geq \kappa_{\text{B0}}$, the system is turned into information priority mode. Thus we should optimize both η_{EEIT} and η_{SEIT}. This working condition is similar to the conventional RF wireless information transfer, there is a trade-off between EE and SE in simple information transfer system [15]. Referring to the above, there is also a trade-off between η_{EEIT} and η_{SEIT} in the SWIPT system. The Nash Bargain Solution (NBS) is involved to optimize the trade-off between η_{EEIT} and η_{SEIT} [16]. According to the NBS, we treat the η_{EEIT} and η_{SEIT} as two game players and use the method of bargaining game to solve the compromised optimization of η_{EEIT} and η_{SEIT}. A NBS is a Pareto Efficient Solution (PES) to a Nash bargaining game [17]. In the bargaining game of η_{EEIT} and η_{SEIT}, the worst situation for η_{EEIT} is setting the system by maximizing the SE, then the threat value a_{EE} for η_{EEIT} could be calculated. Similarly, we can get the threat value a_{SE} for η_{SEIT}. According to the NBS, seeking the PES is equivalent to solving the following optimization problem.

TABLE I: Simulation parameters

Parameter	Value
Switching factor, α	[0,1]
Transmit power, P_{t}	[10,3000] mW
Bandwidth, B	10 MHz
Transmitter circuit power consumption, P_{c}	100 mW
Quasi-static channel, h	0.7
Distance between receiver and transmitter, d	3 m
Signal power attenuation, $\theta = Cd^{-\delta}$	C=-20 dB
Path-loss exponent, δ	3
Noise spectral density, N_0	-111 dBm/MHz
RF to DC convert efficiency, ξ	0.7
Battery power, κ_{B}	30 mAh
The lowest requirement of data rate, R_0	10-250 Mbps
The lowest requirement of harvested power, P_{e0}	5-200 uW

$$[\alpha, P_{\text{t}}] = \arg\max \left\{ (\eta_{\text{SEIT}} - a_{\text{SE}})(\eta_{\text{EEIT}} - a_{\text{EE}}) \right\}. \qquad (17)$$
$$\text{s.t.} \quad \alpha \in [0,1], P_t \in [P_{\text{t,min}}, P_{\text{t,max}}]$$

2) Battery power is insufficient:

When $\kappa_{\text{B}} \leq \kappa_{\text{B0}}$, the system should be turned into energy priority mode, optimizing the system performance is equivalent to maximizing η_{SEEH} and η_{EEEH} of the system. It is easy to prove that η_{SEEH} and η_{EEEH} have the same increase-decrease trend against α and P_{t}. Thus the optimal value of α and P_{t} can be expressed as (16).

IV. SIMULATION RESULTS AND ANALYSES

Main system parameters are summaried in Table I. under the system settings in Table I, the ranges of P_{t} and α under different restricted conditions can be calculated by substituting R_0 and P_{e0} into (9) and (10). As is shown in Fig. 3, where the intersection areas of solid line and dotted line are choosen to be the feasible region for α and P_{t}. It is important to indicate that all the adjustments of α and P_{t} should be done within the feasible zones to ensure the proper function of the system.

A. Battery power is insufficient

According to the above analyses, in spite of the transmit power supply and bandwidth, we should maximize (12) and

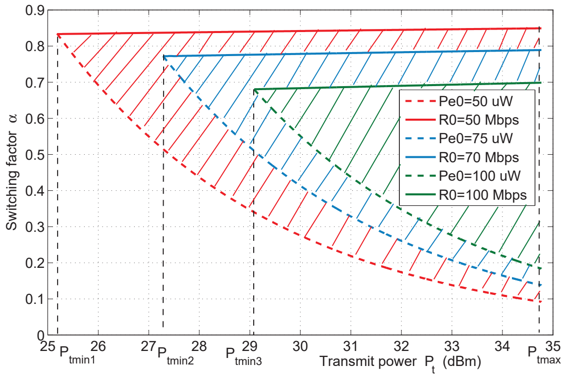

Fig. 3: Feasible regions for P_{t} and α.

(16) in order to get the optimal system performance on condition that battery power is insufficient. It is prone to get the partial derivative of (12), where $\frac{\partial P_{\mathrm{e}}}{\partial \alpha} \geq 0$, $\frac{\partial P_{\mathrm{e}}}{\partial P_{\mathrm{t}}} \geq 0$. Calculating the partial derivative of (16), it can be derived that $\frac{\partial \eta_{\mathrm{EEEH}}}{\partial \alpha} \geq 0$ and $\frac{\partial \eta_{\mathrm{EEEH}}}{\partial P_{\mathrm{t}}} \geq 0$. So that α and P_{t} should be as large as possible to get the optimal system performance. On condition that $P_{\mathrm{e0}} = 75$ uW and $R_0 = 70$ Mbps, the transmit power P_{t} is set to 34.77 dBm and the switching factor α is set to 0.789 under this optimizing strategy.

B. Battery power is abundant

1) Sufficient transmit power supply:

The optimal system settings can be calculated by (11) on condition that there are sufficient transmit power supply and abundant battery for the SWIPT system. It is easy to get the partial derivative of (11), $\frac{\partial R}{\partial \alpha} \leq 0$, $\frac{\partial R}{\partial P_{\mathrm{t}}} \geq 0$, so that P_{t} should be as large as possible and α should be set to the minimum value to get the maximum rate. When $P_{\mathrm{e0}} = 75$ uW and $R_0 = 70$ Mbps, the transmit power P_{t} is set to 34.77 dBm and the switching factor α is set to 0.138 under this strategy.

2) Limited transmit power supply:

When the bandwidth is sufficient, we can calculate the optimal system settings according to (15). When $\frac{\partial \eta_{\mathrm{EEIT}}}{\partial P_{\mathrm{t}}}$ is equal to 0, the value of transmit power P_{t} is settled as $P_{\mathrm{t,ee}}$, this value is the available maximum value of EE for IT η_{EEIT} against transmit power P_{t}. As discussed above, we have a feasible range of transmit power, $P_{\mathrm{t}} \in [P_{\mathrm{t,min}}, P_{\mathrm{t,max}}]$.

As is shown in Fig. 4, when $P_{\mathrm{t,min}} \leq P_{\mathrm{t,ee}} \leq P_{\mathrm{t,max}}$, P_{t} is equal to $P_{\mathrm{t,ee}}$, when $P_{\mathrm{t,min}} \leq P_{\mathrm{t,max}} \leq P_{\mathrm{t,ee}}$, P_{t} is equal to $P_{\mathrm{t,max}}$, when $P_{\mathrm{t,ee}} \leq P_{\mathrm{t,min}} \leq P_{\mathrm{t,max}}$, P_{t} is equal to $P_{\mathrm{t,min}}$ to get the highest EEEH. Under this optimizing strategy, when $P_{\mathrm{e0}} = 75$ uW and $R_0 = 70$ Mbps, the transmit power P_{t} is set to 29.52 dBm and the switching factor α is set to 0.462.

When the bandwidth is limited, we should calculate the optimal system settings according to (17). According to the literature [17], researchers proved that using a_{SE} and a_{EE} as the threat value in (17), can fairly promote η_{SEIT} and η_{EEIT}. Under this working condition, we choose the minimum value of switching factor α referring to (14). So the relational expression between R and P_{t} can be derived from (8)

$$R(P_{\mathrm{t}}) = (1 - \frac{P_{\mathrm{e0}}}{\xi P_{\mathrm{t}} h \theta}) B log_2 (1 + \frac{P_{\mathrm{t}} h \theta}{B N_0}) \tag{18}$$

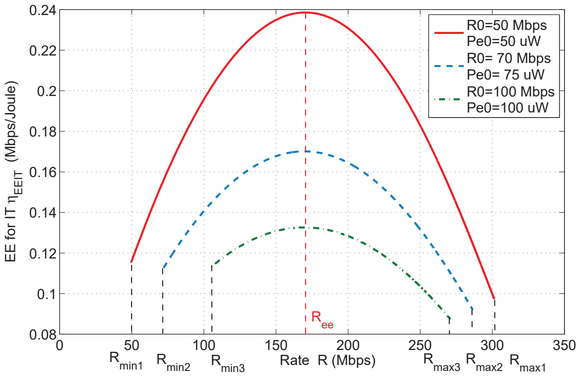

Fig. 5: EE for IT against R.

The function of $\eta_{\mathrm{EEIT}}(R)$ can be obtained by substituting the (14) and (18) into (4). According to the analyses mentioned above, The minimum value of rate R_{min} is equal to R_0, the maximum value of rate can be expressed as R_{max}, and R_{ee} is the rate for maximizing the EE for IT. As is shown in Fig. 5, if $R_{\mathrm{min}} \leq R_{\mathrm{ee}} \leq R_{\mathrm{max}}$, we set the threat value a_{SE} equal to R_{ee} and a_{EE} is equal to R_{max}. Otherwise, we can choose the R_{max} or R_{min} instead of R_{ee}. By substituting (18) into (17), another form of the optimization problem can be derived as

$$\begin{aligned} R_{\mathrm{opt}} &= \arg\max \left\{ (\frac{R}{B} - a_{\mathrm{SE}})(\eta_{\mathrm{EEIT}} - a_{\mathrm{EE}}) \right\} \\ \text{s.t.} \quad & \alpha \in [0,1], P_{\mathrm{t}} \in [P_{\mathrm{t,min}}, P_{\mathrm{t,max}}]. \end{aligned} \tag{19}$$

It is easy to prove that (19) is strictly concave in the feasible region of R. The search region of the optimal solution is $[a_{\mathrm{SE}}, a_{\mathrm{EE}}]$. We can solve (19) to obtain the value of R_{opt}, which is the value of rate for the optimal system performance according to NBS. The optimal values of α and P_{t} can be derived by subtituting R_{opt} into (1).

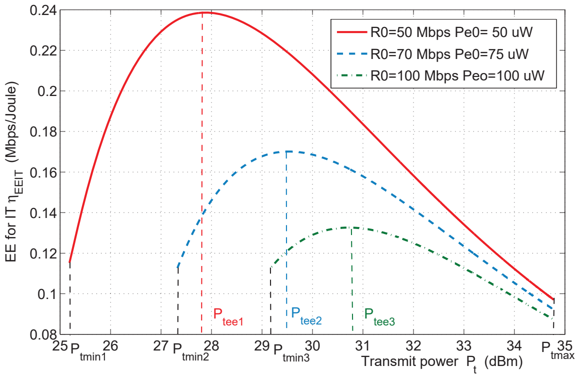

Fig. 4: EE for IT against P_{t}.

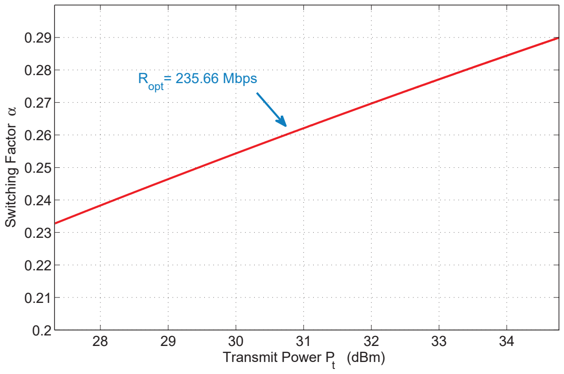

Fig. 6: The optimal system settings for NBS.

As shown in Fig. 5 , on condition that $P_{e0} = 75$ uW and $R_0 = 70$ Mbps, a_{SE} is equal to 16.93 Mbps/Hz , a_{EE} is equal to 0.0923 Mbit/Joule and R_{opt} is equal to 235.66 Mbps. The red line in Fig. 6 is the optimal system settings for the optimal setting of rate R_{opt}. All the values of P_{t} and α within the interval can satisfy the optimal trade-off between η_{SEIT} and η_{EEIT} based on the NBS. The transmit power P_{t} should be set as low as possible with limited transmit power supply. Under this optimizing strategy, P_{t} is set to 27.32 dBm and the α is set to 0.233 to achieve the optimal system performance. As is discussed above, the optimization strategies can adjust the SWIPT system into optimal working situations and have a great reference value for SWIPT system design.

V. CONCLUSIONS

The precise definitions of EE for IT, SE for IT and EE for EH, SE for EH in SWIPT have been presented in this paper. The switching factors and transmit power have been chosen as the key parameters for the SWIPT system. Based on the new definitions, the trade-offs among η_{SEIT}, η_{EEIT}, η_{SEEH}, and η_{EEEH} have been analyzed with varying switching factors and transmit power. Optimal system setting strategies have also been presented to achieve optimal system performance under various working conditions. A practical and efficient SWIPT system can be further designed and the optimal system parameters can be settled according to theoretical results of this paper.

VI. ACKNOWLEDGEMENTS

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