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Point-to-Point Wireless Information and Power Transfer in WBAN With Energy Harvesting

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ABSTRACT In this paper, a point-to-point communication system in a wireless body area network capable of harvesting radio-energy is studied. We investigate two scenarios for transmission, which are in normal circumstance and in abnormal circumstance. We consider power splitting protocol in normal circumstance and time switching protocol in abnormal circumstance at the sensor, respectively. Based on two protocols, the optimal power splitting and time switching ratios are derived in each scenario. The goal of this paper is to maximize the information throughput from the sensor to the access point in uplink by balancing the time duration among the command transfer phase, the energy harvesting phase, and the information transfer phase while satisfying energy harvesting and consumption balance constraint at the sensor. Numerical results demonstrate the effectiveness of the optimal solution.

INDEX TERMS Wireless body area networks (WBANs), throughput maximization, energy harvesting, wireless power transfer.

I. INTRODUCTION

Wireless body area network (WBAN) is a real-time, low-power, short range communication network. A WBAN consists of several different kinds of sensors, which are implanted in or placed on skin, i.e., in-body or on-body, respectively. On-body area networks are used to provide communication between the sensors placed on skin, and in-body area networks can realize the communication between the sensors implanted in skin. It can be applied to medical and personal health care, sports, military, fitness, etc.. These sensors can continuously measure the physiological and contextual parameters profiling the body activities and then the access point (AP) transmits these sensory data to the medical center [1], [2]. IEEE 802.15 (i.e., Task group6) standardize the WBAN scheme, which describes WBAN as *"low power devices operating in or around the human body (but not limited to humans) to serve a variety of applications including medical, consumer electronics/personal entertainment and other"* [3], [4]. In [5], The sensor selection problem in WBAN is considered, which is dissolved by sensor array synthesis algorithm via convex optimization. For the single node and cooperative multiple nodes, spectrum sensing at sub-Nyquist sampling rates to reduce the computational complexity is investigated in [6] and [7]. Human body posture recognition based on WBAN is discussed in [8] and [9]. The authors in [10] propose a game theoretic approach about the interference caused by multiple WBANs located closely to each other in a small area. In [11] and [12], efficient resource allocation for Device-to-Device is considered.

Compared to conventional communication, wireless communication with energy harvesting (EH) is flourishing, and the sensor does not have to consider saving energy at work. Thus optimizing power allocation of sensor nodes with energy harvesting has recently drawn significant research interests, which can improve the efficiency of networks, prolong network lifetime and reduce preservation cost in communications [13]. In [14], the authors investigate the power management strategies for the point-to-point communication powered by EH sources. Under the assumption that the capacity of the battery is infinite or finite, the authors in [15] study the throughput maximization problem for both two cases with a deterministic EH model and a random EH model. In [16], a water-filling energy allocation solution where the so-called water levels follow a staircase is proved to be optimal, which is investigated in energy harvesting with channel fading. The authors in [17] consider the block random EH model, and derive the optimal power allocation polices of the throughput maximization problem via dynamic programming and convex optimization techniques. In WBAN, a mass of sensors consume much energy, and the sensors have limited operation time. When the sensors are exhausted, WBAN will be fail. However, for applications in WBAN replacing batteries is inconvenient or impossible. Thus energy harvesting in WBAN, whereby energy is extracted from body surrounding environment, becomes an alternative solution. The authors in [18] discuss the propagation channel between two half-wavelength dipoles which placed near a human body and presents an application for cross-layer design in order to optimize the energy consumption of different topologies at 2.45 GHz. In [19], the authors make a relatively comprehensive introduction from energy harvesting principle and characteristics to practical application, and analyzed the data communication. The throughput and delay performance of the IEEE 802.15.6 standard is presented in [20], where the authors derive some equations for the maximum throughput and minimum delay.

Recently, the research on the radio frequency energy-based energy harvesting technology with wireless communications has attracted the attention of people. In [21], the power splitting (PS) and time switching (TS) protocol for wireless-powered relaying system with simultaneous energy harvesting and information transmission are considered. The authors in [22] propose a new wireless powered communication (WPC) system with a bidirectional information and energy forwarding relay. In [23], the authors investigate practical receiver designs for simultaneous wireless information and power transfer. Based on dynamic power splitting (DPS), they propose two practical receiver architectures, namely, separated and integrated information and energy receivers. In [24], optimal time allocation for the power receiver to balance wireless power transfer and information transfer has been studied. In [25], under a point-to-point flat-fading SISO channel setup, the authors study simultaneous wireless information and power transfer (SWIPT) via the approach of dynamic power splitting (DPS). The authors in [26] propose a new channel learning algorithm for the point-to-point MIMO WET system. By revising that the energy receiver (ER) sends back to the energy transmitter (ET) only one bit per feedback interval to indicate the increase or decrease of its harvested energy. Assuming channel reciprocity, this paper studies the optimal design of channel training for MIMO WET systems in Rician fading channels. The forward link channel of WET can be efficiently estimated at the ET based on the training signals sent by the ER in the reverse communication link [27].

In recent years, how to use the harvested energy and transfer information efficiently for a point-to-point communication system in WBAN is becoming an urgent and significant research problem. In this paper, we consider the joint command transfer, wireless power transfer and information transfer based on PS and TS protocol, and in this system, sensor transfers command and information with the harvested energy. An optimal information throughput problem with energy harvesting and information transferring is proposed to maximize the throughput in WBAN.

In normal circumstance, we consider power-splitting architecture at the sensor. In the first phase,the AP transmits command signal and energy signal simultaneously, the command-signal only indicates the sensor, and then the sensor transfers information in energy harvesting to the AP. In this system, the information signal block length is the same as the command signal, however, the command signal takes up a small part of the entire information signal block length, which can ensure the information signal to be transmitted successfully. Thus, the time slot should be divided into energy harvesting and information portions. It is significant to determine the optimal command signal time allocation in this system in WBAN. We attempt to derive the trade-off between command and energy harvesting to maximize the throughput while satisfying the energy causality. When this system is in abnormal circumstance, the time-switching protocol is proposed. In the first phase of the time duration, the command-signal is sent from the sensor for harvesting energy. During the second phase, the AP transfers wireless power to the sensor in order to help harvest energy. Based on the received energy-signal, the sensor harvests energy to meet its power need. In the third phase, the sensor transmits information to the AP. With the proposed protocol, under the energy causality constraint, we jointly optimize the time which includes the uplink of command transfer, the downlink of wireless power transfer and the uplink of information transfer, in order to maximize the information throughput of wireless information transmission in the uplink.

The rest of the paper is organized as follows: In Section II, the system model of human body and the channel model are described. In Section III, as for normal circumstance in WBAN, we propose a practical protocol for the considered system based on the power-splitting strategy at the EH sensor, the specific closed-form of power-splitting ratio and maximization throughput are derived. Section IV proposes a practical protocol based on the time-switching strategy at the sensor in abnormal circumstance, and the optimal time-switching ratio is formulated by maximizing the information throughput within energy harvesting. In Section V, simulation results validate the optimization problem. Section VI concludes the paper.

II. CHANNEL MODEL

As shown in Fig.1, we consider a Wireless Body Area Network, where the communication link is in front of torso. According to the IEEE 802.15.6 standard, there are three communication channels, which are described as in-body, on-body, and off-body channels [3]. As for WBAN, channel characterizations is fading, path loss, shadowing and power delay profile.The path loss is usually modeled with the following empirical power decay law [28]:

$$P_{dB} = P_{0dB} + 10n \log (d/d_0) \tag{1}$$

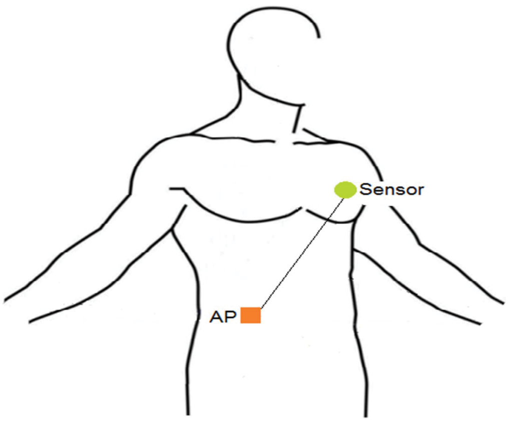

FIGURE 1. The body channel model.

where n denotes the path loss exponent, d is the distance between the AP and the Sensor, d_0 is the reference distance, and P_{0dB} is the path loss at the reference distance.

We assume the AP is equipped with a battery with sufficiently large initial energy, and for simplicity, we assume that the sensor has no fixed power supply and the sensor circuit power consumption is negligible [20], and we must ensure that the energy consumption at reverse (from the sensor to AP) does not exceed the harvested energy of sensor. Under the assumption that perfect channel state information (CSI) is available at sensor, we aim to maximize the information throughout from sensor to AP.

III. NORMAL CIRCUMSTANCE

A. SYSTEM MODEL

As shown in Fig.2, We firstly consider the AP sends energy and command to sensor simultaneously, and then consider the sensor sends information to AP. To receive command and harvesting energy simultaneously, the sensor employs a power-splitting architecture [23].

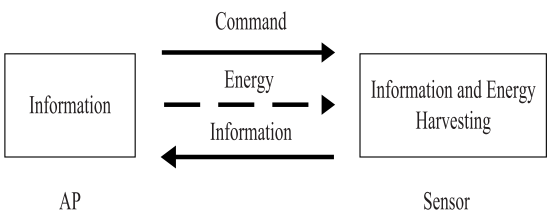

FIGURE 2. The communication channel model in normal circumstance.

As shown in Fig.3, in the first phase of duration T/2, the AP transmits command-bearing signal and energy-bearing signal simultaneously to sensor. Upon receiving a signal y_s at sensor, it splits the signal into two parts with power ratio ρ $(0 \le \rho \le 1)$: one is used for energy harvesting to replenish its battery, and other is used for information processing. The signal received at sensor during the first phase is given by

$$y_s = \sqrt{P_a} h x_a + n_s \tag{2}$$

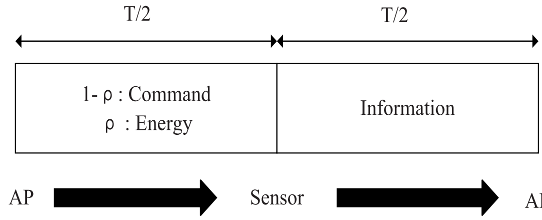

FIGURE 3. Protocols for communication channel model in normal circumstance.

where x_a is a transmitted signal that is known to the sensor. P_a represents the transmit power of the AP. h denotes the downlink channel coefficient from the AP to sensor, which is assumed to be Rayleigh fading. n_s is the antenna noise at sensor. The average energy harvested at sensor during each block is given by

$$E = \eta\rho E\left[|y_s|^2\right](T/2) \approx \eta\rho P_a |h|^2 (T/2) \tag{3}$$

where $E[\bullet]$ denotes the statistical expectation, we have ignored the noise n_s. because we aim to the energy harvested at sensor due to $P_s \ll P_a$. η $(0 \le \eta \le 1)$ denotes the energy conversion efficiency for the energy harvesting circuit at sensor. The other split signal at sensor can be given by

$$y_s' = \sqrt{1-\rho}\left(\sqrt{P_a} h x_a + n_s\right) \tag{4}$$

In the second phase of duration T/2, the sensor only transmits information-bearing signal. Thus, the signal transmitted by sensor during the second phase can be expressed as

$$x_s = \sqrt{\mu}\left(\sqrt{1-\rho}\left(\sqrt{P_a} h x_a + n_s\right) + n_s'\right) \tag{5}$$

where μ is the coefficient of amplify-and-forward at sensor. n_s' is the sensor noise modeled as a zero-mean complex Gaussian random variable with variance σ_n^2 and represents the additional processing noise at sensor, which is assumed to dominate the antenna noise n_s ; Thus, n_s is ignored for simplicity. The received signal at the AP during the second phase is given by

$$y_a = \sqrt{P_s} g x_s + n_a \tag{6}$$

where n_a is the AP noise modeled as a zero-mean complex Gaussian random variable with variance σ_a^2 and denotes additive noise at the AP, g denotes the channel coefficients in the uplink(from sensor to AP) channel. P_s represents the transmit power of the sensor in normal circumstance. μ is the coefficient of amplify-and-forward at sensor, and μ must ensure the energy harvesting and uplink consumption balance constraint at sensor, i.e.,

$$E_s \le E \tag{7}$$

where $E_s = E\left[|y_a|^2\right](T/2)$ is the minimum required power to transmit information at sensor. Since the maximum power that can be harvested is P_a. We can simplify the energy harvesting inequality constraint to an equality constraint, i.e., $E_s = E$, which ensures that sensor transmits information and make the information throughput is further increased. Thus, with E given in (2), we have

$$\mu = \frac{\eta \rho P_a |h|^2}{(1-\rho) P_s |g|^2 + \sigma_n^2} \tag{8}$$

In this paper, the received signal at the AP during the second phase also can be given by $y_a = g\sqrt{\mu}\left(\sqrt{1-\rho}\sqrt{P_a} h x_a + n_s'\right) + n_a$. The resulting signal-to-noise(SNR) can be given by

$$\gamma(P_s, \rho) = \frac{(1-\rho)\mu |h|^2 |g|^2 P_a}{|g|^2 \mu \sigma_n^2 + \sigma_a^2} \tag{9}$$

On the other hand, the signal received at the AP from the sensor is y_a. and the energy consumed maximum at the sensor is $\eta^2 \rho P_a |h|^2 |g|^2 (T/2)$. Furthermore, as the signal-to-noise(SNR) $\gamma(P_s, \rho)$ given in (9) monotonically decreases with P_s for any fixed ρ, P_s should be set to its maximum possible value, which is achieved as

$$P_s = \frac{\eta^2 \rho P_a |h|^2 |g|^2 (T/2)}{T/2} = \eta^2 \rho P_a |h|^2 |g|^2 \tag{10}$$

Note that in (10) , the transmission power at the sensor is proportional to the AP transmission power due to double channel attenuations h and g, power splitting ratio ρ. Thus we have $P_s \ll P_a$. As a result, the end-to-end information throughput from the sensor to the AP is

$$R(P_s, \rho) = \frac{1}{2}\log_2\left(1 + \frac{(1-\rho)\mu |h|^2 |g|^2 P_a}{|g|^2 \mu \sigma_n^2 + \sigma_a^2}\right) \tag{11}$$

B. PROBLEM FORMULATION

We only focus on the end-to-end throughput at the AP and consider the following optimization problem: how to optimally split ρ the power of the received signal during both down link and up link so that the information throughput is maximized while maintaining an acceptable energy harvesting rate, i.e.,

$$\begin{aligned} &\max_{\rho} \quad R(P_s, \rho) \\ &s.t.\ \ 0 \le \rho \le 1 \end{aligned} \tag{12}$$

It is clear that the power-splitting parameters affect the information throughput only through signal-to-noise (SNR), ρ^* can be given by

$$\begin{aligned} &\max_{\rho} \quad \gamma(P_s, \rho) \\ &s.t.\ \ 0 \le \rho \le 1 \end{aligned} \tag{13}$$

As for (13), with some simple manipulations and after discarding constant terms, ρ^* can be obtained by solving

$$\begin{aligned} &\min_{\rho} \quad \frac{1}{(1-\rho)^2} + \frac{W(2\rho - 1)}{\rho^2 (1-\rho)^2} \\ &s.t.\ \ 0 \le \rho \le 1 \end{aligned} \tag{14}$$

where $W \triangleq \frac{\sigma_a^2}{|h|^2 |g|^2 \eta P_a}$. As the object function of (14) at the extreme point $\rho = 0$ and $\rho = 1$ approach to infinity, and the optimal solution must be within the open interval (0, 1), which can be obtained by finding stationary points via solving equation $\rho^2 + 2W\rho - W = 0$. So we can obtain the optimal power splitting ratio ρ^* in close-from as

$$\rho^* = -W + \sqrt{W^2 + W} \tag{15}$$

Proof: See Appendix.

IV. ABNORMAL CIRCUMSTANCE

A. SYSTEM MODEL

As shown in Fig.4, we focus on the design of a point-to-point wireless powered system in WBAN. When the sensor in WBAN is in abnormal circumstance, the sensor sends command to the AP for energy requirement, and then the AP sends wireless energy to sensor, and then consider the sensor sends information to AP by leveraging energy. There is a power receiver (denoted by sensor) that can play the roles in both a power receiver and an information transmitter. It is assumed that all the nodes aforementioned are equipped with a single antenna. It is further assumed that the AP has a constant power supply. Hence, it does not need other energy sources. However, the sensor has no fixed power supply. We aim to maximize the information throughout from sensor to AP.

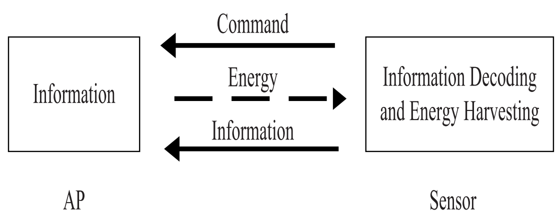

FIGURE 4. The communication channel model in abnormal circumstance.

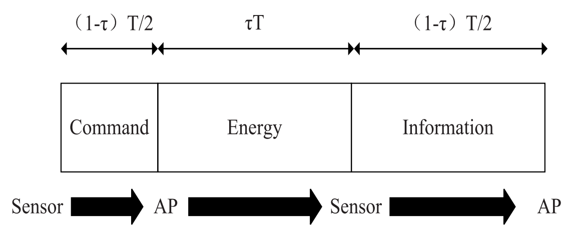

FIGURE 5. Protocols for communication channel model in abnormal circumstance.

As shown in Fig.5, we propose a three-phase protocol for WBAN by leveraging the channel reciprocity property. In the first phase of $(1-\tau)T/2$ symbol durations with $0 \le \tau \le 1$, the command-signal is sent from the sensor to AP for warning the sensor in abnormal. The received signal at the AP can be expressed as

$$y_{a1} = \sqrt{P_{s,ab}} g x_{sc} + n_a \tag{16}$$

where y_{a1} denotes the received signal at the AP. x_{sc} stands for the command-signal of the sensor, and $P_{s,ab}$ represents the transmit power of the sensor. x_{sc} is a signal satisfying $E\left[|x|^2\right] = P$, so the average energy consumed at the sensor in the uplink (from the sensor to the AP) can be expressed as

$$E_{sc} = E\left[|y_{a1}|^2\right]((1-\tau)T/2) \\ = \left(P_{s,ab}|g|^2+\sigma_n^2\right)((1-\tau)T/2) \quad (17)$$

Based on the received command-signal, the AP begins to respond. During the second phase τT symbol durations, the AP transmits energy-bearing signals to sensor with power P_a. With similar analysis as in the previous section, the received signal at the sensor can be given as

$$y_{s,ab} = \sqrt{P_a}hx_a + n_s \quad (18)$$

According to (18), the total energy harvested at the sensor during each block is given by

$$E_{s,ab} = \eta E\left[|y_{s,ab}|^2\right]\tau T \approx \eta P_a|h|^2\tau T \quad (19)$$

In the third phase of the duration $(1-\tau)T/2$, the sensor forwards an amplified signal to the AP, which can be achieved as

$$y_{a2} = \sqrt{P_{s,ab}}gx_{si} + n_a \quad (20)$$

where x_{si} is the information-signal of the sensor, and with (20), the average energy consumed by the information-signal at the sensor in the uplink (from the sensor to the AP) can be expressed as

$$E_{si} = E\left[|y_{a2}|^2\right]((1-\tau)T/2) \\ = \left(P_{s,ab}|g|^2+\sigma_n^2\right)((1-\tau)T/2) \quad (21)$$

In this paper we consider the case when all of the harvested energy is used for information. The average energy consumed at the sensor in the uplink (from the sensor to the AP) should satisfy the energy harvesting constraint at each block in the entire system. We thus have

$$\mu_s(E_{sc} + E_{si}) \leq E_{s,ab} \quad (22)$$

where μ_s denotes the amplification coefficient to satisfy the energy consumption. According to (22), we have

$$\mu_s \leq \frac{2\eta P_a|h|^2\tau}{\left(P_{s,ab}|g|^2 + \sigma_n^2\right)(1-\tau)} \quad (23)$$

In the third phase of the duration $(1-\tau)T/2$, the sensor forwards an amplified signal c $y_{a2}=g\sqrt{\mu_s}\left(\sqrt{P_a}hx_a + n_s'\right) + n_a$ to the AP. With similar analysis as in the Section III, the received SNR at the AP can be expressed as

$$\gamma_{ab}\left(P_{s,ab},\tau\right) = \frac{\mu_s P_a|h|^2|g|^2}{|g|^2\mu_s\sigma_n^2+\sigma_a^2} \quad (24)$$

Since $\gamma_{ab}\left(P_{s,ab},\tau\right)$ monotonically decreases with $P_{s,ab}$ for any fixed τ, $P_{s,ab}$ should be set to its maximum possible value while satisfying the energy consumption and harvesting balance constraint. i.e., $\eta|g|^2\mu_s E\left[|y_{a2}|^2\right]((1-\tau)T/2) = \tau\eta^2P_a|h|^2|g|^2T$, which yields

$$P_{s,ab} = \frac{\tau\eta^2P_a|h|^2|g|^2T}{(1-\tau)T/2} = \frac{2\tau\eta^2P_a|h|^2|g|^2}{1-\tau} \quad (25)$$

And the end-to-end throughput from the sensor to the AP is

$$R_{ab}\left(P_{s,ab},\tau\right) = \frac{1-\tau}{2}\log_2\left(1+\frac{\mu_s P_a|h|^2|g|^2}{|g|^2\mu_s\sigma_n^2+\sigma_a^2}\right) \quad (26)$$

Note that in (26), for convenience, we simplify the (22) inequality constraint to an equality constraint. By substituting (23) and (25) into (26), the end-to-end information throughput as a function of τ can be expressed as

$$R_{ab}(\tau) = \frac{1-\tau}{2}\log_2\left(1+\frac{1}{D_1+D_2(1-\tau)/\tau}\right) \quad (27)$$

where $D_1 \triangleq \left(\sigma_a^2\eta+\sigma_n^2\right)/\left(P_a|h|^2\right)$ and $D_2 \triangleq \sigma_a^2\sigma_n^2/\left(2\eta P_a^2|h|^4|g|^2\right)$.

B. PROBLEM FORMULATION

Here, we focus on formulating an optimization problem to achieve the tradeoff in this system. It is worth noting that the total time is limited. If less time is allocated to send command and more time is allocated to harvest energy, higher available transmission power can be obtained. It is what WBAN needed, and we can get a higher throughput in this system. Thus, to maximize the throughput of the system in WBAN, time allocation between three phases should be optimized. i.e.,

$$\max_{\tau} \quad R_{ab}(\tau) \\ s.t. \quad 0 \leq \tau \leq 1 \quad (28)$$

From the objective function (27), the optimal time ratio for throughput maximization is then given by $\tau^* = \arg\max_{0\leq\tau\leq1} R_{ab}(\tau)$, which can be obtained numerically via one-dimensional searching. According to WBAN power characteristics, to gain some insights, we consider the extreme case with $P_a \to 0$. In this case, $D_1/D_2 \propto P_a$, i.e., d_1 is dominated by D_2 and thus D_1 can be neglected. The optimization problem can be solved through the optimization algorithm. The first order of (27) necessary condition is equal to zero, the optimal solution of (27) is given as follows

$$\ln\left(1+\frac{\tau^*}{D_2(1-\tau^*)}\right) = \frac{1}{\tau^*+D_2(1-\tau^*)} \quad (29)$$

With Lambert W function, which is defined by $z = W(z)e^{W(z)}$, the optimal τ^* can be obtained as

$$\tau^* = \frac{1-d_2(1+q^*)}{1-d_2(1+q^*)+q^*} \quad (30)$$

where q is defined a new variable $q \triangleq (1-D_2)(1-\tau)/(\tau+D_2(1-\tau))$, it can be verified that $q^*=W(c)$, where $c \triangleq \exp(-1)(1/d_2-1)$. In this WBAN system, it follows that $P_a \to 0$, and thus $D_2 \to \infty$, so we have symbol durations $\tau T \rightarrow T$, it satisfies that the first phase which is used to send abnormal command and the second phase used to harvest energy, and hence most of time should be allocated for information processing.

V. SIMULATION RESULTS

In this section, the simulation results are presented. Numerical results are provided to verify the normal circumstance and abnormal circumstance schemes in WBAN. According to body surface to body surface channel model [4], the following path loss model is based on measurements that cover frequencies of 3.1-10.6 GHz. Depending on the location of the AP and the sensor and the parameters of path model are extracted from the measurements [4], [28], the path-loss model in front of the torso is the function of the distance d_a and d_r. The downlink channel gain distribution h and the uplink channel gain distribution g can be given as $|h|^2 = 10^{-4.46-3.1log\left(\frac{d_a}{10}\right)}$ and $|g|^2 = 10^{-4.46-3.1log\left(\frac{d_r}{10}\right)}$. d_a is the downlink channel reference distance, and $d_r = d-d_a$ is the uplink channel reference distance. For the purpose of exposition, we assume that the AP and the sensor in normal circumstance and in abnormal circumstance are separated by fixed distance $d_{normal} = 2$ and $d_{abnormal} = 0.4$ meters (m), which are the AP and the sensor reference distance in WBAN. According to the IEEE 802.15.6 standard, we assume that the maximum transmit power of the AP P_a is 1mW, and the coefficient of the energy conversion is $\eta = 1$. The duration of each time slot, the noise power σ_a^2 is assumed to be -174dBm and σ_n^2 is assumed to be -60dBm.

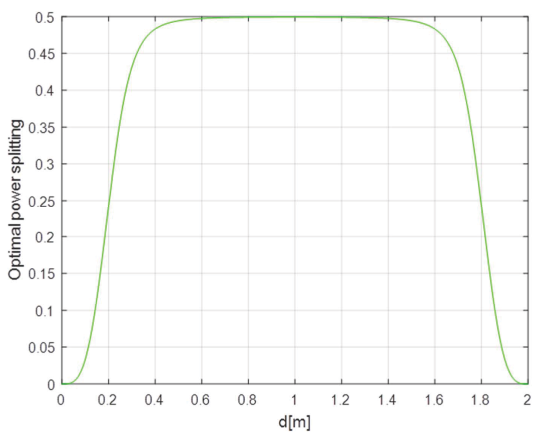

FIGURE 6. The optimal power-splitting ratio ρ^* in normal circumstance versus d.

A. NORMAL CIRCUMSTANCE

We firstly look at the power-splitting design in normal circumstance. Fig.6 shows that the optimal power splitting ρ^* is plotted against d . It is observed that when the distance between the AP and the sensor is in the interval [0.6,1.4], the optimal power-splitting ratio is around 0.5, whereas its value increases as the AP moves near to the sensor and decreases as the AP moves far to the sensor . This can be verified to be in accordance with section III.

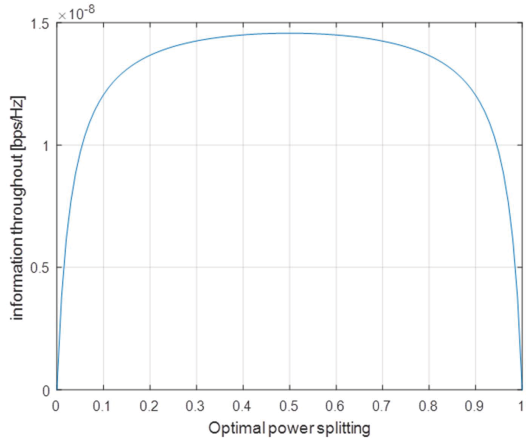

FIGURE 7. Information throughput $R(\tau)$ in normal circumstance versus power-splitting ratio ρ.

Fig.7 demonstrates the relationship between information throughput $R(\tau)$ and power-splitting ratio ρ from (11) under no constraint. We set d_a=d_r = 1m. In this figure, we can see that, in the interval [0, 0.5], the throughput increases with ρ , and in the interval [0.5, 1], the throughput decreases with the increase in ρ. This implies that there exists a unique optimal power-splitting ratio.

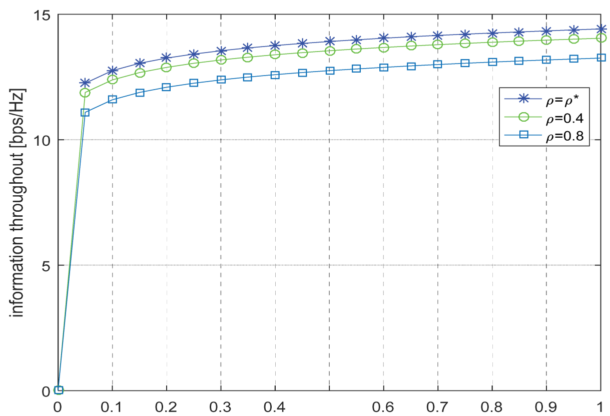

FIGURE 8. Information throughput $R(\tau)$ in normal circumstance versus transmission power P_a under different power-splitting ratio ρ.

In Fig.8, we compare the information throughput performance between the optimal and the fixed power-splitting policies. Generally, the throughput performance is notable, particularly when the power-splitting ratio is optimal. This confirms that it is important to differentiate the optimal power-splitting ratio and fixed ratio when designing the power-splitting policy for good throughput performance.

B. ABNORMAL CIRCUMSTANCE

Fig.9 depicts the relation between the optimal time switching ratio and the distance d. As it is shown and is expected, the optimal time switching ratio first increases and then decreases as the AP moves near to the sensor. The optimal

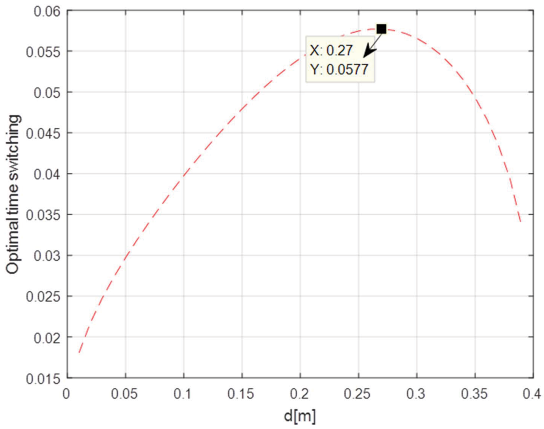

FIGURE 9. The optimal time-switching ratio τ^* in abnormal circumstance versus d.

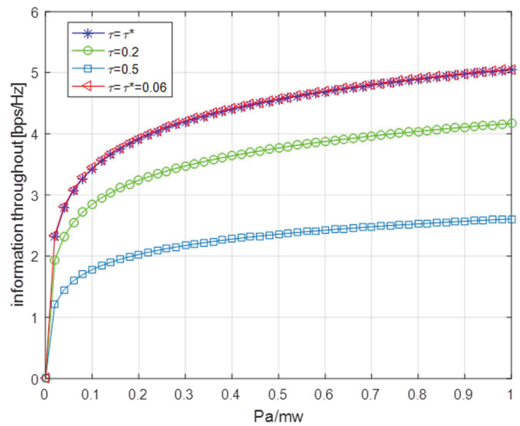

FIGURE 11. Information throughput $R_{ab}(\tau)$ in abnormal circumstance versus transmission power P_a under different time-switching ratio τ.

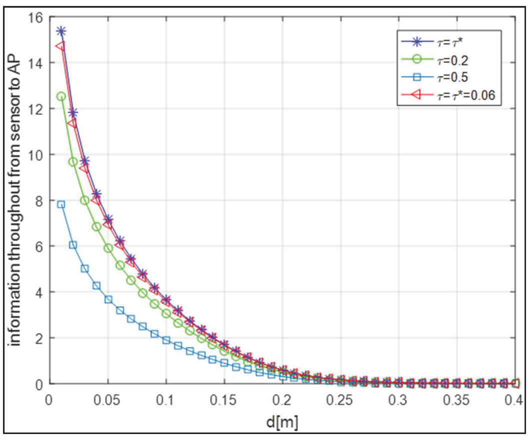

FIGURE 10. Information throughput $R_{ab}(\tau)$ under different time-switching ratios in abnormal circumstance versus d.

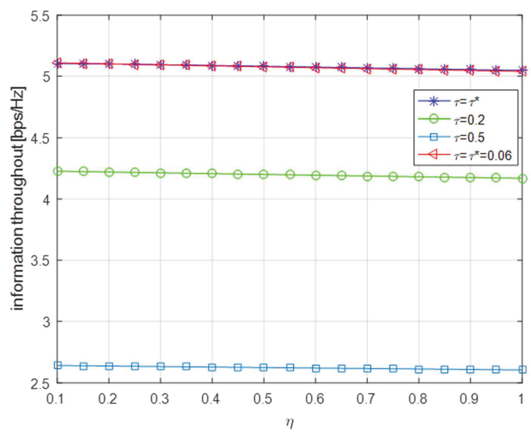

FIGURE 12. Information throughput $R_{ab}(\tau)$ in abnormal circumstance versus η under different time-switching ratio τ.

time switching ratio τ^* is around 0.057 . The optimal time-switching ratio τ^* is calculated in section IV. The numerical results agree with our theoretical analysis. The comparison of the maximum information throughput $R_{ab}(\tau)$ in different time-switching ratio τ^* in abnormal circumstance against d is depicted in Fig.10. It is obvious that when the distance is far, the information throughput difference is not notable, and when the distance is close, the values are different from each other. As d increases, the power gain decreases. This means that the channel condition is going to become bad, which leads to the decrease in the throughput. When the time-switching ratio τ is optimal, the throughput is higher than that under the fixed time allocotion.

Fig.11 reports the comparison results of the throughput under the optimal time-switching ratio τ^*, time-switching ratio τ=0.2 and time-switching ratio τ=0.5 versus different values of transmission power P_a in the interval [0,1mw]. We set $d_{abnormal}$=0.2m. As shown in Fig.11, the information throughput under the optimal time switching ratio is greater than other time switching ratio. Fig.12 demonstrates the comparison results of the throughput versus the coefficient η of the energy conversion in different time-switching ratio. With η increases, the information throughput has little change, and when the optimal time-switching ratio is τ^*, the throughput is higher than others.

VI. CONCLUSION

In this paper, an information throughput maximization of point-to-point link in WBAN over path loss channel model with energy harvesting is considered. In this case, we focus on the design of a power-splitting protocol in normal circumstance and a time-switching protocol in abnormal circumstance, respectively. The optimal power splitting policies and the optimal time switching policies in point-to-point transmission are derived. Then, an optimization problem in this system is proposed to maximize the information throughput with energy constraint. Additionally, numerical results in different system parameters are provided to verify that our proposed point-to-point designs in WBAN are reasonable.

APPENDIX
PROOF FOR THE OPTIMAL POWER SPLITTING RATIO OF EQUATION (15)

By taking equation (10) into equation (8), we can get

$$\mu = \frac{\eta\rho P_a|h|^2}{(1-\rho)\,\eta^2\rho P_a|h|^2|g|^4 + \sigma_n^2} \tag{31}$$

By taking equation (31) into equation (9), we can get

$$\gamma(\rho) = U\frac{(1-\rho)\rho}{\rho + V\rho(1-\rho) + W} \tag{32}$$

Where $U \triangleq \frac{|h|^2P_a}{\sigma_n^2}$, $V \triangleq \frac{\sigma_a^2|g|^2}{\eta\sigma_n^2}$ and $W \triangleq \frac{\sigma_a^2}{|h|^2|g|^2\eta P_a}$. To get the optimal power splitting ratio ρ^*, the function of ρ can be given as

$$f(\rho) = \frac{(1-\rho)\rho}{\rho + V\rho(1-\rho) + W} \tag{33}$$

It also can be given by $f(\rho) = \frac{1}{1/(1-\rho)} + V + W/(\rho(1-\rho))$ Now by calculating the first derivative of the $g(\rho) = 1/(1-\rho) + V + W/(\rho(1-\rho))$, the $g(\rho)'$ is achieved as

$$g(\rho)' = \frac{1}{(1-\rho)^2} + \frac{W(2\rho-1)}{\rho^2(1-\rho)^2} \tag{34}$$

From (34), the optimal power splitting ratio ρ^* can be given by equation (15).

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