Joint Power-Rate-Slot Resource Allocation in Energy Harvesting-Powered Wireless Body Area Networks

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***Abstract*—Wireless body area network (WBAN) has become a promising network for continuous health monitoring of various diseases. The limited energy of sensors in WBAN cannot support the long term work with the high requirements of Quality of Service (QoS) for health applications. Energy harvesting (EH)-powered WBAN, which can provide uninterrupted work, has attracted more attention from both macadamia and industry. However, the time-varying and heterogeneous EH states of different sensors become an important factor when designing the resource allocation schemes in EH-powered WBAN. In this paper, we propose a novel two-phase resource allocation scheme, which optimizes the allocation of transmission power, source rate and slots to improve the QoS performance of EH-powered WBAN. In the first phase, we analysis the relationship between the QoS performance and the source rate for satisfying the Energy Neutral Operation (ENO), and then a joint Power-Rate Control Scheme (PRCS) is proposed to optimize the source rate and transmission power for ensuring the long-term QoS performance based on the statistical properties of EH. Moreover, we design a QoS Aware Slot Allocation Scheme (QASAS) to dynamically adjust the time slot allocation to cope with the time-varying and heterogeneous EH states for obtaining better short-term QoS performance in the second phase. Finally, numerical simulation results demonstrate that the proposed joint the Power-Rate-Slot resource allocation scheme of EH-powered WBAN can effectively exploit the time-varying EH to improve both long-term and short-term QoS performance.**

***Index Terms*—energy harvesting, resource allocation, wireless body area network (WBAN).**

I. Introduction

With the rapid development of sensor and wireless communication technologies, wireless body area network (WBAN) can replace complex and wired healthcare requirement to continuously monitor the body's vital signals and provide real-time feedback to the user and doctors without causing any discomfort and interrupting their daily lifestyle [1–3]. WBAN typically consists of several lower-power, miniaturized and lightweight on-body or implanted sensor nodes to monitor physiological parameters, which are collected and further transmitted to remote medical servers by one energy-efficient hub (Mobile phone or PDA) for various medical and healthcare applications [4]. Generally, most of these applications are life critical and require a long lifetime without interrupting user's daily lifestyle, while still have a strict guarantee of Quality of Service (QoS) in terms of packet loss, delay and so on [5].

However, the limited battery capacity, constrained by the size and weight of sensors nodes, cannot support the long term operation without interruption. Besides, replacing battery or taking off sensors to charge power is not always practical especially for some implanted sensors, which also causes the interruption of the health monitoring system [6, 7]. Although the classical energy saving technologies make efforts to explore different energy efficient schemes in aspects of MAC protocol design, power control schemes and cross-layer resource scheduling strategies to prolong the system lifetime [4, 8, 9], the ultimate goal 'uninterrupted work' cannot be ensured. Fortunately, Energy Harvesting (EH) technology, which can collect energy from various sources around human body, has recently been considered as a promising solution to overcome the bottleneck of energy limited WBANs [10]. For instance, EH-powered sensors can scavenge energy from a variety of limitless ambient sources (e.g., light, heat, electromagnetic radiation) or the body itself (e.g., locomotion, breathing, heartbeat, lactate), and then convert it to usable electric energy for providing continuous power [11]. Thus, EH-powered WBANs have the potential ability to achieve infinite lifetime and perpetual operation, which is called Energy Neutral Operation (ENO) [12]. Furthermore, sensors can also combine several types of EH sources for acquiring more energy to support more strict QoS requirements [6]. Therefore, researchers pay more and more attentions on how to keep in ENO state with considering the QoS performance in EH-powered WBAN.

Due to the limitation of the sensor size, the energy harvester cannot always satisfy the ENO requirement and the collected energy is scarce. In addition, sensors in different positions on the body may have different types of EH and the energy collection rates are heterogeneous. Meanwhile, harvesters with energy sources from the human body have time-varying states caused by the dynamic body movement status. Thus, the time-varying and heterogeneous EH states become a significant factor to design the effective resource allocation scheme for ENO state. Therefore, it is highly meaningful to do some resource management researches on EH-powered WBAN with considering the QoS performance.

A. Related works

Compared with EH-powered wireless sensor networks (WSNs), the human body contains more bio-energy sources besides the ambient source for various kinds of energy harvesters in WBANs [13]. Generally, these bio-energy sources

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can be classified into biochemical and biomechnical energy sources. The biochemical energy sources convert electrochemical reactions to electricity for implanted body sensors, while the harvesters can scavenge energy from the voluntary and involuntary actions of the human body as biomechnical energy sources [11]. The scavenged energy can be converted to electric potential by appropriated harvesters, and then stored into a rechargeable battery or a super-capacitor for powering up wireless body sensors [14]. The energy harvesting efficiency can be improved to harvest more energy through the elaborate hardware circuit design [15][16]. Therefore, the available power density by harvesting energy from human body gradually reaches μW range, which will be able to run low-low-power-consuming wireless devices, such as Bluetooth4.0 [17], MicaZ [18], MultiMode [19] and so on. However, the harvesting process of human body sensors is unstable and time-varying due to the dynamic body movement status [10]. In addition, the different positions of sensors or different types of energy harvesters have heterogeneous energy harvesting rates. Therefore, the resource allocation scheme for EH-powered WBAN should be able to cope with time-varying and heterogeneous EH states for better utilizing the scavenged energy.

In the literature, some researches have been focused on the resource allocation schemes for EH-powered WBANs. Generally, these resource allocations schemes can be divided into two categories in terms of the priori knowledge of the channel state, data state and energy state for the transmitter, i. e. the offline schemes [20–23] and the online schemes [6, 13, 24–29]. For the offline schemes, it is assumed that the transmitter have perfect priori knowledge of the channel state, data state and the energy state when it allocates resources [13]. In [23], the short-term throughput and the transmission completion time were regarded as the objective function to obtain the optimum power allocation with a deadline constraint and finite energy storage capacity, while energy arrivals were assumed as a priori known. Shan et al. [22] proposed a general framework to transform the continuous-rate model into practical discrete transmission rates with keeping the optimality, and the per-application quality-of-service (QoS) could be guaranteed by the optimal rate scheduling algorithm for an EH enabled transmitter, assuming that the information regarding packets and harvesting is known in advance. Varan et al., [21] considered the throughput maximization problem with finite energy and data storage constraints, and new notions of water pumps and overflow bins were added to the directional waterfilling for solving the energy scheduling problem. In [28], the weighted sum of the outage probabilities was the objective function to minimize in the power control policy, while the harvested energy was known as a priori to the scheduler. However, due to the non-convex objective function, a near-optimal offline scheme was designed with only high signal-to-noise ratios. The above offline resource allocation schemes commonly construct the convex optimization problems and analytical solutions to obtain the optimal resource allocation results with perfect non-causal and priori knowledge. Thus, offline schemes can only serve as a benchmark of the resource allocation schemes, or the EH states are predictable for some stable energy sources.

Compared with the offline schemes, only the causal information and statistical knowledge of energy states, data states and channel states can be utilized in the online schemes to manage the data packets and the collected energy. Ozel et al., [29] maximized the number of bits sent by a deadline given only the distributions of the energy arrivals and channel fade levels. Leng and Yener [13] maximized the long-term expected throughput under the energy constraints, and the close-form expression of optimal transmission power was obtained by formulating the Largrangian and solving the KKT conditions. However, these long-term throughput cannot meet the specific application requirements for these heterogeneous body sensors in WBANs. In addition, the QoS requirements are not carefully taken into consideration in the optimization problems. Liu et al., [27] modeled the transmission power and time allocation optimization problem as a Markov decision process (MDP) to provide a sustainable and high quality service for EH-powered WBAN. However, MDP based resource allocation schemes have the high complexity for wireless devices with limited computational capabilities in WBANs, and they are highly dependent on the accuracy models of channel fading level, energy arrivals and data arrivals, which are hardly obtained in practice. To achieve the best possible QoS, authors of [6] proposed a joint power-QoS control scheme for making optimal use of harvested energy to efficiently transmit the respective data packets of only one sensor in WBAN. However, the channel fading was not considered in the scheme, which could not deal with the dynamic link characteristics in WBANs. In addition, the time-varying and heterogeneous EH states of different body sensors were not considered.

B. Contributions

In this paper, we develop an efficient resource allocation scheme for EH-powered WBANs to support both the long-term and short-term QoS requirements, when the energy harvesting states of different body sensors are heterogeneous and time-varying. The important contributions of this paper are expressed as three aspects:

1) As far as we know, this work is the first to joint the transmission power, source rate and time slots to effectively allocate the resources under dynamic link characteristics of heterogeneous body sensors with the time-varying EH states. Therefore, the harvested energy can be efficiently utilized to improving both the long-term and short-term QoS performances.
2) We analyze the relationship between the source rate and the long-term QoS performance of a body sensor for satisfying the Energy Neutral Operation (ENO). Then, we optimize the transmission power and the source rates for different body sensors to improve the long-term QoS performance, which is based on the statistical knowledge of energy harvesting and channel fading. An optimal numerical solution is successfully obtained through the transformation of the non-convex problem.
3) The time-varying and heterogeneous EH states will cause the fluctuation of the data queues, which affect the

short-term QoS performance. Thus, we carefully predict the states of each sensors based on the energy states and queue states, and then dynamically adjust the time slot allocation to better transmit data packets with harvesting energy for improving the short-term QoS performance.

The remainder of this paper is organized as follows. In Section II, the system model is presented. In Section III, the relationship between the source rate and the QoS peformance is described in details, and a join power and source rate optimization allocation problem is formulated and solved. In Section IV, the sensor states are evaluated based on the energy state and queue buffer state, and a short-term QoS aware slot allocation scheme is provided in details. In Section V, the numerical results are discussed and analyzed. Finally, Section VI concludes the paper.

II. System model

In this section, we give the details of node's architecture and WBAN topology in EH-based WBAN. Then, the energy harvesting model is introduced. Finally, the energy consumption model is correspondingly obtained with the dynamic link characteristics.

A. Node's Architecture and WBAN Topology

We consider a classical WBAN which consists of one hub and N EH-powered wireless sensor nodes. Suppose that the hub (such as PDA and mobile phone) has sufficient resources to implement some resource allocation scheme with high computation complexity, and the wireless sensor nodes placed in different positions of the body have limited processing and storage resources with energy harvesters. The set of body sensor nodes is expressed as $\mathcal{C}_{node} = \{1, 2, \cdots, N\}$. As recommended by IEEE 802.15.6 [30], the body sensor nodes collect the vital signals and communicate directly with the hub considering the constrained resources of sensor nodes in a star topology. In addition, a scheduled access mechanism in beacon mode with superframe boundaries is adopted to access the channel without collisions, idle listening and overhearing of sensor nodes for saving scarce energy. One superframe is formed by one beacon and M slots, and the set of slots are expressed as $\mathcal{C}_{slot} = \{1, 2, ..., M\}$. In the beacon of superframe, the hub broadcast the beacon packets to configure the transmission rates, source rates and dedicate time slots for each nodes. And the nodes only turn active in its dedicate time slots to transmit data signals, and turn sleep in other slots for saving energy. In each node, the vital signals are collected and packetized in the data queue, which will be transmitted to the hub with the First-In-First-Out (FIFO) queue strategy and the retransmission strategy [31]. Thus, the packet losses only occur in two situations: data queue overflow and the delay over the preset threshold.

B. Energy Harvesting Model

Due to the different positions and functions of different sensor nodes, the adopted energy harvesters may collect energy from different energy sources. For instance, the sensor node on the foot can utilize the piezoelectric transducer to harvest energy from the body motion [32], and the sensor node for capturing the electrocardiograph (ECG) signal may use a thermoelectric generator to harvest from the body temperature [33]. Therefore, the EH states of different nodes are heterogeneous. In this paper, the harvested energy is stored in a rechargeable battery or a super-capacitor, then used to power the body sensor node [11]. The EH process of each node can be model as a correlated discrete-time Markov chain with two state: the active state (ON) and the inactive state (OFF) [6, 34]. And the coherence time of the EH process is set to the $k \cdot t_{slot}$, where t_{slot} is the time length of one time slot in superframe. In the ON state, the energy acquisition rate follows an uniform distribution in range of $[EH_{min}, EH_{max}]$, which is based on intensity of body movement. In addition, the energy acquisition rate in the ON state are different for different sensor nodes. In the OFF state, the energy harvester does not collect any energy. The Markov chain of EH process is shown in Fig. 1. p_{01} means the transition probability from OFF state to ON state, while p_{10} represents the transition probability from ON state to OFF state. The probability of keeping ON state and OFF state are regarded as $p_{11} = 1 - p_{10}$ and $p_{00} = 1 - p_{01}$, respectively. Thus, the transition matrix can be expressed as follows,

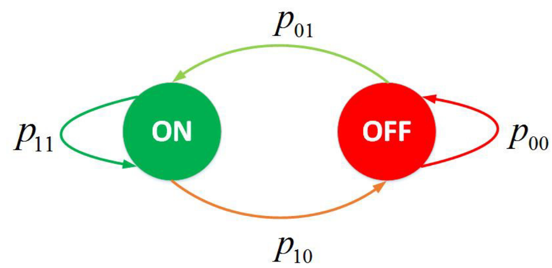

Fig. 1: Discrete Two-state Markov Chain of the EH process

$$\mathrm{P} = \begin{bmatrix} 1 - p_{01} & p_{01} \\ p_{10} & 1 - p_{10} \end{bmatrix} \tag{1}$$

Then, the steady probabilities of ON state and OFF state are expressed as follows,

$$\mu_{on} = \frac{p_{01}}{p_{01} + p_{10}} \tag{2}$$

$$\mu_{off} = \frac{p_{10}}{p_{01} + p_{10}} \tag{3}$$

C. Energy Consumption Model

In body sensor nodes, most of the energy is consumed to transmit data packets and recieve ACK packets, while the energy consumption of the processing and beacon listening can be ignored [35]. Generally, the transmission energy consumption consists of two parts: the transmit amplifier energy consumption E_{tx} and the circuitry energy consumption E_{ct} [31, 36]. Thus, the energy model of transmitting packets can be expressed as follows,

$$E_{tran} = (1 + \alpha) E_{tx} + E_{ct} \tag{4}$$

Compared with the energy consumption of transmitting packets, the energy model of receiving packets only contains the circuitry energy consumption E_{ct}.

$$E_{rec} = E_{ct} \tag{5}$$

where α means the power amplifier inefficiency factor, $E_{tx} = P_{tx}t$ and $E_{ct} = P_{ct}t$. P_{tx} represents the transmission power of the transmitter, and P_{ct} is the circuitry power, which is a constant depending on the specific transmitter [37].

To improve the QoS requirementsthe transmission power should be dynamically adjusted to cope with the time-varying link quality. Thus, the path loss model of wireless links become a important factor for the energy consumption. In this paper, the path loss model $PL\left(d\right)$ for both Light-Of-Sight (LOS) and None-Light-Of-Sight (NLOS) scenarios follows the log normal distribution as recommended by IEEE 802.15.6 [30].

$$PL\left(d\right) = PL_{d_0} + 10n\log_{10}\left(\frac{d}{d_0}\right) + X_\sigma \tag{6}$$

where PL_{d_0} is the path loss at the referent distance d_0, and n represents the path-loss exponent. The shadowing X_σ follows the normal distribution $\mathcal{N}\left(0, \sigma_s^2\right)$, and the statistic characteristics are related to the human postures and the environments [38][39].

III. Long-term Power-Rate Control Scheme

In this section, the analysis of the relationship between the source rate and the QoS performance is first given in details. Then, the join power and source rate optimal allocation are formulated as a optimization problem. Finally, the optimal numerical solution is given through the convex transformation.

A. Relationship between Source Rate and QoS performance

As we known, the higher the source rate is, the more energy it needs to be transmitted. When the harvested energy cannot support the current source rate, the packet loss rate of packets will occur. Conversely, the energy will accumulate with the . Thus, the source rate should be dynamically adjusted to the statistic feature of EH process for satisfying the Energy Neutral Operation (ENO). We have three cases on the relationship between the source rate and the QoS performance:

Case 1: When the harvester with minimum energy acquisition rate $EH_{\min}$ in the ON state still can collect enough energy to transmit the packets in a long term, it means the perfect QoS performance can be obtained under the Energy Neutral Operation (NEO).

$$0 < \left[\left(1+\alpha\right)P_{tx} + P_{ct}\right] \cdot \frac{S \cdot T}{R} \le \mu_{on} \cdot EH_{\min} \cdot T \tag{7}$$

$$\Rightarrow 0 < S \le \frac{\mu_{on} \cdot EH_{\min} \cdot R}{\left[\left(1+\alpha\right)P_{tx} + P_{ct}\right]} \tag{8}$$

where R is the transmission rate, and T is the time length of one superframe. If the above inequality can be satisfied, the collected energy is enough to transmit all packets in a long term. Thus, the QoS performance of packets can be guaranteed through the effective resource allocation scheme.

Case 2: When the required energy harvesting rate for the source rate is in range of $\left[EH_{min}, EH_{max}\right]$ of the ON state, it means the packet losses may occur due to the time-varying EH states.

$$\mu_{on} \cdot EH_{\min} \cdot T < \left[\left(1+\alpha\right)P_{tx} + P_{ct}\right] \cdot \frac{S \cdot T}{R} \le \mu_{on} \cdot EH_{\max} \cdot T \tag{9}$$

$$\Rightarrow \frac{\mu_{on} \cdot EH_{\min} \cdot R}{\left[\left(1+\alpha\right)P_{tx} + P_{ct}\right]} < S \le \frac{\mu_{on} \cdot EH_{\max} \cdot R}{\left[\left(1+\alpha\right)P_{tx} + P_{ct}\right]} \tag{10}$$

If the source rate satisfies the above inequality, there may be some packets blocked in the data queue. The blocked packets need to be dealt with carefully in the resource allocation scheme, otherwise the short-term QoS performance will become worse.

Case 3: When the maximum energy acquisition rate $EH_{\max}$ cannot support the source rate, it means the packet losses are sure to appear due to the insufficient energy.

$$\mu_{on} \cdot EH_{\max} \cdot T < \left[\left(1+\alpha\right)P_{tx} + P_{ct}\right] \cdot \frac{S \cdot T}{R} \tag{11}$$

$$\Rightarrow \frac{\mu_{on} \cdot EH_{\max} \cdot R}{\left[\left(1+\alpha\right)P_{tx} + P_{ct}\right]} < S \tag{12}$$

If the source rate satisfies the above inequality, there must be some packets blocked in the data queue. The resource allocation scheme needs to carefully schedule resources to improve the QoS performance.

B. Join Power and Source Rate Optimal Allocation Problem

With the statistic knowledge of the EH process, the achievable source rate in the dynamic link characteristics should be obtained to better configure the final source rate with little distortion for effective diagnostic, while the long-term QoS constraints are also fully taken into consideration.

In the resource allocation scheme, the packet loss rate (PLR) as the main QoS metrics is studied. The PLR can be expressed as the function of the bit Signal to Noise Ratio (bit SNR),

$$PLR(\gamma) = 1 - \left(1 - P_{b,B}(\gamma)\right)^L \tag{13}$$

where bit SNR can be calculated as $\gamma = 10^{\frac{P_{tx,dB} - PL(d) - P_N}{10}} \frac{B}{R}$. L is the length of a packet in bits. $P_{tx,dB}$ is the transmission power in dB. P_N is the power of noise. B represents the system bandwidth. $P_{b,B}$ indicates the equivalent bit error rate based on the modulation and the channel coding [40].

In this paper, we investigates the allocation of the source rate and the transmission power under the constraints of the QoS performances by constructing the following join power and source rate optimization problem:

$$\textbf{P1:} \quad \max_{P_{tx,i}, S_i} \sum_{i=1}^{i \in \mathcal{N}} S_i, \tag{14a}$$

$$s.t. \quad \sum_{i=1}^{i \in \mathcal{N}} S_i \cdot T \le R \cdot T, \tag{14b}$$

$$0 \le \frac{S_i}{1 - PLR_{i,th}}, \tag{14c}$$

$$\frac{S_i}{1 - PLR_{i,th}} \le \frac{\frac{EH_{i,\max} + EH_{i,\min}}{2} \cdot \mu_{on} \cdot R}{\left[\left(1+\alpha\right)P_{tx,i} + P_{ct,i}\right]}, \tag{14d}$$

$$\overline{PLR_i} \leq PLR_{i,th}, \tag{14e}$$

$$P_{tx,\min} \leq P_{tx,i} \leq P_{tx,\max}, \tag{14f}$$

where $PLR_{i,th}$ is the threshold of the packet loss rate for node i. $\overline{PLR_i}$ represents the average packet loss rate with the allocation transmission power P_i. $P_{tx,min}$ and $P_{tx,max}$ are the minimum value and the maximum value of the transmission power for the transmitter, and we assume all the nodes have the same type transmitter for the sake of simplicity.

C. Optimal Numerical Solution

D. Soure Rate Configuration

IV. Short-term QoS Aware Slot Allocation Scheme

A. Energy Harvesting Process Analysis

B. Sensor state evaluation

C. Slot Allocation Scheme for Energy-Sufficient Nodes

D. Slot Allocation Scheme for Energy-Constraint Nodes

V. Simulation results

A. Simulation Setup

B. Simulation Results of Power-Rate-Slot Control Schemes

C. The Influence of Different EH Efficiencies on Performance

D. The Influence of Different Mean of Shadowing on Performance

VI. Conclusion

In this paper,

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