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

Zhiqiang Liu, *Student Member, IEEE*, Bin Liu, *Member, IEEE*, and Chang Wen Chen, *Fellow, IEEE*

***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

Zhiqiang Liu is with the Key Laboratory of Electromagnetic Space Information, Chinese Academy of Sciences, Department of Electrical Engineering and Information Science, University of Science and Technology of China, Hefei 230027, China (e-mail: lzhq28@mail.ustc.edu.cn).

Bin Liu is with the Key Laboratory of Electromagnetic Space Information, Chinese Academy of Sciences, School of Information and Technology, University of Science and Technology of China, Hefei 230027, China (e-mail: flowice@ustc.edu.cn).

Chang Wen Chen is with Department of Computer Science and Engineering, University at Buffalo, State University of New York, New York 002837, USA (e-mail: chencw@buffalo.edu).

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

III

IV

II. System model

This is system model

A. Energy Consumption Model

B. Energy Harvesting Model

III. Long-term Power-Rate Control Scheme

A. Relationship between Source Rate and Uninterrupted Lifetime

B. Join Power and Source Rate Optimal Allocation

C. Optimal Analytical Solution

D. Soure Rate Configuration

IV. Short-term QoS Aware Slot Allocation Scheme

A. Energy Harvesting Process Analysis

B. Node state evaluation

C. Slot Allocation Scheme for Energy-Sufficient Nodes

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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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Zhiqiang Liu received the B.S degrees in electrical engineering from University of Science and Technology of China, Hefei, Anhui, China, in 2013, and he is currently pursuing the Ph.D. degree in electrical engineering from University of Science and Technology of China. His research interests lie resource allocation, energy-saving and Quality of Service guarantee in wireless body area networks.

Bin Liu received the B.S. and M.S. degrees, both in electrical engineering, from University of Science and Technology of China, Hefei, Anhui, China, in 1998 and 2001, respectively, and the Ph.D. degree in electrical engineering from Syracuse University, Syracuse, NY, in 2006. Currently, he is an Associate Professor with the School of Information Science and Technology, University of Science and Technology of China. His research interests are signal processing and communications in wireless sensor and body area networks.

Chang Wen Chen (F'04) is a Professor of Computer Science and Engineering at the State University of New York at Buffalo, USA. Previously, he was Allen S. Henry Endowed Chair Professor at Florida Institute of Technology from 2003 to 2007, a faculty member at the University of Missouri - Columbia from 1996 to 2003 and at the University of Rochester, Rochester, NY, from 1992 to 1996. He has been the Editor-in-Chief for IEEE Trans. Multimedia since 2014. He has also served as the Editor-in-Chief for IEEE Trans. Circuits and Systems for Video Technology from January 2006 to December 2009 and an Editor for Proceedings of IEEE, IEEE TMM, IEEE JSAC, IEEE JETCAS, and IEEE Multimedia Magazine. He and his students have received eight (8) Best Paper Awards or Best Student Paper Awards and have been placed among Best Paper Award finalists many times. He is a recipient of Sigma Xi Excellence in Graduate Research Mentoring Award in 2003, Alexander von Humboldt Research Award in 2009, and SUNY-Buffalo Exceptional Scholar - Sustained Achievements Award in 2012. He is an IEEE Fellow and an SPIE Fellow.