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An Adaptive Energy Efficient MAC Protocol for RF Energy Harvesting WBANs

Juncheng Hu, Gaochao Xu, Liang Hu, Shujing Li, Yang Xing, *Member, IEEE,*

***Abstract*—Continuous and remote health monitoring medical applications with heterogeneous requirements can be realized through wireless body area networks (WBANs). Energy harvesting is adopted to enable low-power health applications and long-term monitoring without battery replacement, which have drawn significant interest recently. Because energy harvesting WBANs are obviously different from battery-powered ones, network protocols should be designed accordingly to improve network performance. In this article, an efficient cross-layer media access control protocol is proposed for radio frequency powered energy harvesting WBANs. We redesigned the superframe structure, which can be rescheduled by the coordinator dynamically. A time switching (TS) strategy is used when sensors harvest energy from radio frequency signals broadcast by the coordinator, and a transmission power adjustment scheme is proposed for sensors based on the energy harvesting efficiency and the network environment. Energy efficiency can be effectively improved that more packets can be uploaded using limited energy. The length of the energy harvesting period is determined by the coordinator to balance the channel resources and energy requirements of sensors and further improve the network performance. Numerical simulation results show that our protocol can provide superior system performance for long-term periodic health monitoring applications.**

***Index Terms*—WBAN, MAC protocol, energy efficiency, RF energy harvesting.**

I. Introduction

Since the beginning of mankind, people have been plagued by various diseases. Although cures for some diseases have been found thanks to the rapid development of modern medicine, chronic diseases such as heart disease, cerebrovascular disease and cancer are still the top killers of humans [1], [2]. If these diseases are detected in a timely manner or early in the incubation period, the patient survival time can be significantly prolonged after standardized treatment [3]. Even for most diseases that can be cured, timely treatment in the early stage has a better curative effect; moreover, the suffering of patients can be obviously reduced. Therefore, the prevention and early detection of diseases is essential. A method capable of continuous and remote monitoring of human health status is needed to evaluate the healthy state in a timely manner; thus, wireless body area networks (WBANs) have received extensive attention as one of the most promising technologies for health care monitoring.

As a special wireless network that consists of a few wearable, implantable, or portable biosensors, tiny, lightweight, smart, and low-power sensor nodes are developed to perform personal health care applications that sense and collect data from a human's body and forward it to the health care center for further analysis. Most sensors are battery-powered, the advantages of which are a stable power supply that can support large data uploading in a short period of time and stable data transmission of remote sensors. Event-triggered emergency applications can also be supported. However, the process of battery replacement or charging will reduce the quality of the user experience, and continuous monitoring of health data cannot be achieved during this period. Meanwhile, the size of the sensors will increase when configuring batteries, and obsolete batteries may pollute the environment. Since the size and weight of each battery powered sensor are strictly limited, the lifetime can hardly be extended by deploying larger batteries. Researchers have attempted to prolong the lifetime of sensor nodes by optimizing the media access control (MAC) protocol [4]–[6], route protocol [7]–[11], sleep schedule [12]–[14], transmission power [15]–[17], etc. However, the lifetime of a node still remains bounded even if the above techniques are deployed, since the battery capacity is finite. Then, energy harvesting (EH), converting ambient (e.g., solar, thermal, vibration and radio frequency) energy to electrical energy, has emerged as an alternative to power sensor nodes [18]. This technology can solve the problem of battery limitation and achieve an infinite lifetime and perpetual operation.

For different ambient energy sources, radio frequency (RF) energy is more suitable for WBANs than others, since solar, thermal and vibration powered EH systems are not very reliable and highly variable when deployed on the human body. Compared with battery powered sensors, RF energy harvesting sensors can provide better user experience quality and are suitable for long-term periodic health status monitoring without burst transmission requirements of large amounts of data. When configuring a WBAN, the network architecture and technologies used can be selected according to the medical application requirements. Meanwhile, network protocols should be carefully designed to ensure network performance, including the MAC protocol which plays a vital role in minimizing transmission collisions and idle listening with limited energy supplies. Many MAC protocols have been designed for WBANs previously, but most of them are dedicated to battery-

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(emails: jchu19@mails.jlu.edu.cn, xugc@jlu.edu.cn, hul@jlu.edu.cn, lsj202jlu@163.com, yang.x@cranfield.ac.uk.)

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powered WBANs. Few of them are designed for EH WBANs, but no power adaptive MAC layer protocol specifically for RF-powered EH WBANs has been proposed yet.

There are some problems should be resolved when designing MAC protocol for RF-powered EH WBANs. Firstly, one issue that needs special attention is the adequacy of harvested energy. Assume that the average energy required by sensor n_i is R_i, and n_i can harvest H_i energy per unit time when the coordinator transmits RF energy, then, sensor n_i can harvest just enough energy when time for the coordinator to transmit energy is R_i/H_i. When the energy harvesting time is too short, n_i will not harvest enough energy to upload packets, which will reduce its performance. On the contrary, when the coordinator uses too much time to charge the sensors which exceed their demand, the human body will absorb unnecessary radiation and may have a potentially adverse impact on the human body. Thus, the coordinator should transmit proper energy according to the sensors' requirements.

Secondly, energy efficiency must be improved to optimize the network performance. The number of successfully received packets per unit of energy is used to measure the energy efficiency, which is affected both by the packet reception ratio and the number of uploaded packets. A higher packet reception ratio can be gained by increasing the transmission power since the coordinator can receive packets with higher SNR. But fewer packets will be uploaded if the usable energy is insufficient. Energy efficiency cannot be maximized when too few packets are uploaded, even if all these packets can be received successfully. On the contrary, more packets can be uploaded when the lower transmission power is adopted, but energy efficiency still cannot be maximized if the packet reception ratio is too low. For sensor n_i with insufficient energy, there is a suitable transmission power $P_i^\star$ to maximize the energy efficiency. When it uses power greater than or less than $P_i^\star$, the number of packets received by the coordinator will decrease due to the reduction of the number of uploaded packets or the packet reception ratio. Therefore, each sensor should choose optimal transmission power according to its transmission requirements and the amount of usable energy to optimize energy efficiency.

Meanwhile, wireless spectrum and energy resources need to be coordinated and scheduled to improve the overall performance of the network. Although the harvestable amount of power is sufficient to power up typical wireless sensor platforms and achieve self-sustainable operability by optimizing the duty cycle of the systems, the available average energy density of ambient wireless sources is relatively lower than other energy sources [19]. Then, data upload is limited by available energy and spectrum resources at the same time. It is difficult for the coordinator to forecast when sensors need to upload data, and reasonable utilization of channel resources is crucial to ensure network performance. Thus, the MAC layer protocol must be designed accordingly since it is responsible for priority control, channel resource allocation and transmission collision detection, which is another critical issue that needs attention to enable efficient and reliable RF-powered EH WBANs.

To solve the problems mentioned above, this paper proposes an adaptive scheduling RF-powered EH-WBAN scheme, which mainly focuses on the MAC layer protocol and power adjustment schemes. Requirements such as data uploading, comprehensive scheduling, sleep scheduling and energy harvesting are all considered when designing the MAC layer protocol. The redesigned superframe is composed of six major phases that include the beacon period, EH period, reservation period, assignment period, upload period and sleep period. The time switching (TS) strategy [20] is used for the energy harvesting process implemented in the EH period, and sensors harvest energy from RF signals transmitted by the coordinator. The lengths of the upload period and EH period are adjusted by the coordinator according to the data transmission requirement and the network throughput. A transmission power adjustment scheme is also given to enable sensors to choose the optimal power according to the EH efficiency and network environment. The principal contributions of this work are highlighted as follows:

- In this paper, we design a new MAC protocol for RF-powered EH WBAN. Considering the characteristics of the network, a TDMA-based scheduling scheme is adopted to avoid transmission collision and idle listening. A modified superframe structure is designed with six periods that can meet the transmission requirements of RF signal energy, health information, and coordination data among nodes. To our knowledge, our protocol is the first power adaptive MAC protocol designed for RF-powered EH WBAN.
- We develop a power adjustment scheme that optimizes the transmission power of sensors to maximize energy efficiency. When a sensor uploads packets with limited energy, improper (either too high or too low) transmission power cannot achieve optimal performance. We give a calculation method of a reference value that is correlated with the current packet reception rate to guide the adjustment of the transmission power. The formulation of optimization solution models that optimizes the trade-off between transmission frequency and packet arrival probability.
- We also propose a superframe adjustment scheme to optimize network traffic throughput and ensure the reliability of the communication. The coordinator counts the sensors' requirements for RF signal energy and wireless channel resources and further calculates the optimal duration of the periods in the superframe. The proposed adjustment scheme can balance the requirements of sensors and optimize the resource utilization of the network.

The rest of this paper is organized as follows. The related works are shown in Section II. Then, section III presents the system model. Section IV introduces the system architecture of the proposed hybrid MAC protocol, including superframe partition, time slot management, adaptive power control and superframe length adjustment schemes. Simulation results are presented in Section V, while section VI concludes the paper.

II. Related Works

The IEEE 802.15.6 [21] standardization is a dedicated communication standard designed for WBAN, which supports low power, short range and reliable wireless communication within the surrounding area of the human body. Many protocols and schemes have been proposed based on IEEE 802.15.6 to improve the energy efficiency, prolong the system lifetime and guarantee the quality of user experience. In this section, we highlight some works related to this paper, which correlated with energy harvesting, MAC protocol and power adjustment schemes.

A. *Energy harvesting*

As a promising technology with self-sustainable energy sources for WBANs. Various EH techniques can be used in WBANs, and ambient energy sources can be transformed into an electrical signal using energy harvesters, including radio frequency energy, which can be provided constantly and stably by the coordinator node.

A QoS-aware energy management scheme is proposed in [22], which enables the optimal use of the energy to assure the strict requirements of vital health signals in terms of QoS. Several potential energy-harvesting sources for wireless body area networks are reviewed in [23], these sources can be harnessed using appropriate hardware and converted to electrical form to fulfill energy requirements. Relay assistant RF-powered WBAN is considered in [24], relay nodes harvest energy from the received signals and consume the harvested energy to forward received information. A three-level sleep scheduling strategy for EH-WABNs is introduced in [25], both energy saving strategy and energy harvesting strategy are considered to prolong the network lifetime. A multi-point WBAN with RF energy harvesting for normal and abnormal scenarios is studied in [26], sum-throughput maximization problems, related optimization algorithms are also proposed. Cognitive radio technology is adopted to improve the spectrum utilization in [27], an overlay model is studied whereby both the primary and secondary communications are realized on the human body through a cooperative spectrum sharing technique.

The existing research work mainly focuses on maximizing the physical layer throughput, and no mac layer protocol is well designed for RF-powered EH WBANs. In fact, the joint optimization of the MAC layer and the physical layer is beneficial to better realize the improvement of the overall network efficiency.

B. *Power adjustment*

Power exhausted by data transmission is one of the most energy consuming operations for sensors. Dynamic adjustment of the transmission power according to the channel state is a proper way to improve the energy efficiency.

Because human motion is one of the dominant factors that affect the channel characteristics in WBAN, a motion-aware temporal correlation model-based transmission power control is proposed in [28] to realizing reliable and energy-efficient WBAN communication. An individual WBAN scenario, focusing on finding an adaptive time slot allocation and power control scheme to maximize the average energy efficiency is considered in [29], a deep reinforcement learning-based scheme to make a sequence decision for the decision process. A Transmission Power Control and packet scheduler mechanism combined is proposed in [30], which takes advantage of Neural Networks and Fuzzy Inference Systems for modelling nonlinear dynamical systems to describe the on-body channel. LSTM-based neural network prediction method is used in [31] to predict the wireless channel, and an interquartile range based power control scheme is proposed for the channel prediction.

Most of the schemes are deployed on the coordinator since it is difficult to realize the prediction of the channel state for sensors, which is limited by the available resources. Relatively stable periodic data are used as the input of existing channel prediction methods, and complex prediction algorithms are generally deployed on the coordinator.

C. *MAC protocol*

A prioritized dedicated slot allocation mechanism using the Criteria Importance Through Inter-criteria Correlation (CRITIC) is proposed in [32], the priority value of sensor devices is calculated based on different sensors' parameters. In order to satisfy multiple performance requirements of WBANs, a priority ladders-based resource scheduling scheme is proposed in [33], four priorities are designed to meet requirements of different nodes. A-MAC [34] redesigned the superframe structure and the priority levels to improve the network adaptability and energy efficiency. AT-MAC [35] propose an adaptive MAC-frame payload tuning mechanism to maximize the probability of successful packet delivery or reliability of the associated sensor nodes based on real-time situation. A MAC protocol is proposed in [36] to tackle the QoS and energy efficiency challenges, transmission order and transmission duration can be adjusted dynamically based on the TDMA scheme, new synchronization scheme is also considered to reduce overhead. A slotted ALOHA and TDMA schemes combined way is used in [37], which proposes a hybrid MAC protocol that can efficiently and effectively optimize the communication channel access of a WBAN multi-class system. A temporal convolution network (TCN) based deep learning approach is adopted for channel prediction in [38], which can improve the network performance in dynamic environment, and TDMA-based superframe structure is used to avoid transmission collision. Distinct sizes of the backoff periods are considered in [39] to reduce packet collisions during carrier sense, an alternative combination of the backoff and CCA adaptation mechanisms is proposed to improve the network performance. In order to meet the higher priority requirement of the emergency data, protocols link I-MAC [4] and EEEA-MAC [5] are designed based on IEEE 802.15.6 to handle emergency events. A duty cycle MAC scheduling protocol [40] is used to predict the original state of the sensors, and then the time-slots are allocated for avoiding packet loss and re-transmission in edge assisted 5G environment WBAN.

These protocols are mainly designed for battery-powered WBANs, and the optimization goal is to improve network performance. There is no need to consider energy constraints for battery-powered nodes, but energy should be harvested before data transmission for EH-powered sensors. Packets can

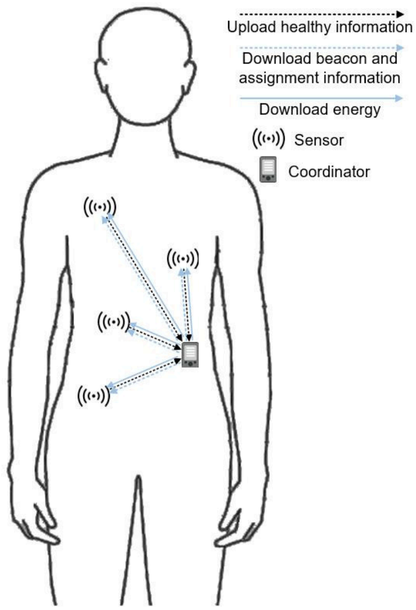

Fig. 1. The network model.

be uploaded only when the accumulated energy is sufficient; therefore, existing protocols are not suitable for RF-powered EH WBANs.

III. Network Model

Fig. 1 illustrates an analytical model for the proposed WBAN in which one coordinator $\mathcal{C}$ and N on-body sensor nodes form a one-hop star network. All the nodes are single-antenna devices and work in the half-duplex scheme. We assume that the coordinator has a fixed power supply and transmits data or RF energy signals separately using the TS scheme with constant power P_c. Sensors are RF-powered EH nodes placed in different positions of the body, and each sensor is equipped with an EH circuit that can convert the received RF power to direct current (DC). Each sensor is an energy-constrained node equipped with a supercapacitor, and energy must be harvested and stored before data transmission. Thermal noise at each node is assumed to be zero mean additive white Gaussian noise (AWGN). The path loss model with distance dependency following the log-normal distribution can be described by the equation [41]–[43].

$$PL(d) = PL(d_0) + 10nlog_{10}(\frac{d}{d_0}) + S, \tag{1}$$

where d_0 denotes the reference distance, $PL(d_0)$ denotes the path loss at the referent distance d_0, n and S represent the path-loss exponent and the shadowing factor.

Typically, a sensor can be in five modes of operations, namely, transmission state (Tx), reception state (Rx), idle state, sleep state and EH state. Most of the harvested energy is consumed to transmit packets and receive data, while energy consumed during the idle and sleep states can be ignored. Sensors reserve time slots only when there are packets that need to be uploaded and turn to the Tx state if new time slots are assigned by the coordinator. The Poisson distribution is used as the packet arrival model, and the probability that k packets are generated during time t is:

$$Pr(k) = \frac{(\lambda t)^k e^{-\lambda t}}{k!} \tag{2}$$

where λ is the packet arrival rate. Once a new packet is generated and an old packet of the same type has not been uploaded, the old packet will be dropped.

IV. Proposed protocol

The main goal of the proposed work is to design a cross-layer MAC protocol for RF-powered EH WBANs. The detailed design of protocol majorly focuses on a) superframe structure and operation process; b) time slots management; c) adaptive power control for sensors; and d) superframe adjustment scheme.

A. *Superframe structure and operation process*

In this section, the proposed superframe for RF energy harvesting powered WBAN is presented in detail. Time is partitioned into repetition intervals of fixed duration known as superframe as shown in Fig. 2(a) and (b). Each second contains M superframes. The superframe is divided into beacon period (BP), reservation period (RP), assignment period (AP), EH period (EP), upload period (UP) and sleep period (SP). Length of each period is dynamically set by the coordinator according to the data transmission and EH requirements.

During the BP, $\mathcal{C}$ broadcasts a beacon message to sensors in the WBAN containing information about the current superframe and time synchronization. Sensors can reserve time slots during the RP if needed, an approach of combining sensing and black-burst broadcast is used to improve the efficiency of time slots acquisition. Resource allocation results are broadcast by $\mathcal{C}$ during the AP. Then, sensors harvest RF energy which can be stored in a super capacitor during the EH period. Time is divided into slots in the UP, sensors upload packet during UP using slots assigned by $\mathcal{C}$. Nodes sleep during the SP to save energy.

Fig. 2(a) illustrates an operation procedure within two superframes of two sensors n_a and n_b. Sensors turn to Rx state in BP and AP to receive beacon and assignment information broadcast by $\mathcal{C}$, turn to EH state to harvest energy during EH period, turn to Tx state to upload packets or transmit reservation information during UP and RP, turn to sleep state after data uploading or after energy harvesting (no packet need to be uploaded), and remain idle state between above mentioned operation modes.

Time is usually divided into energy harvesting period and data uploading period in the TS scheme [26], [27], sensors harvest energy first and upload packets during fixed time slots without channel estimate and power adjustment. Because no cooperation scheme is deployed, sensors cannot choose the proper transmission power to optimize energy efficiency, and the coordinator cannot maintain the network when sensors join or leave the network. Meanwhile, each sensor occupies fixed time slots even if no packets need to be uploaded, which may waste the wireless channel resources.

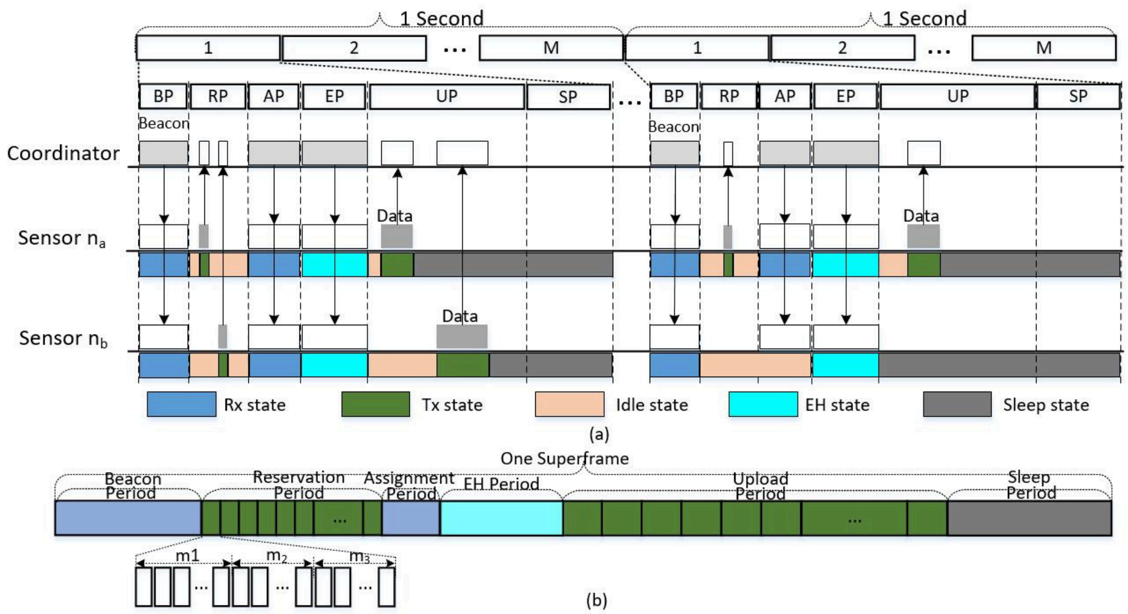

Fig. 2. Superframe division and illustration of the opration process.

BP, RP, AP and SP are added in our scheme to enable cooperation between nodes, which may increase the overhead of the network since fewer wireless channel resources can be used to transmit energy or health information, and sensors need to use energy to enable the cooperation process. But sensors can upload packets using adaptive transmission power, which can improve energy efficiency and network performance. Meanwhile, sensors acquire time slots only when needed instead of occupying fixed time slots. The network is more flexible and robust through the cooperation between nodes.

B. Time slots management

Sensors reserve slots during the RP, and an approach of combining sensing and black-burst broadcast [44] is used to improve the efficiency. The TDMA scheme is employed to reduce transmission collisions and idle listening during the UP, the coordinator assigns time slots to sensors according to their reservation, and sensors only upload packets using assigned time slots. When a sensor needs to reserve new time slots, it randomly chooses one competition slot and performs the sensing and black-burst broadcast combined method to complete the competition.

The reservation period is divided into competition slots, and each competition slot contains Q mini-slots. We divide the Q mini-slots into three parts of length m_1, m_2 and m_3 ($Q = m_1 + m_2 + m_3$) corresponding to the packet priority, sensor identification and number of time slots needed. Sensors choose to broadcast a black burst signal (corresponding to binary number one) or sense the channel (corresponding to binary number zero) during each mini-slot; then, actions for Q mini-slots correspond to an integer in the interval $[0, 2^Q-1]$. One principle that must be obeyed is that once a sensor chooses to sense the channel during a mini-slot and a black burst signal is sensed, the sensor will remain silent in the remaining mini-slots of the current competition slot.

Taking Fig. 3 as an example, m_1, m_2 and m_3 are all equal to 3, and three nodes participate in a competition with chosen values 010100101, 010010101, and 001101011. Node n_3 has the lowest priority value and senses black bursts in the second mini-slot. Nodes n_1 and n_2 have the same priority, the identification of n_2 is smaller, and n_2 senses a black burst in the fourth mini-slot. Both n_2 and n_3 quit the competition after sensing black-burst signals. Node n_1 senses no black burst during all the sensing mini-slots and can transmit all the information successfully. The coordinator can successfully receive the reservation sent by n_1 during the current competition slot.

Integer values I_i^1 $(1 \leq I_i^1 \leq 2^{m_1}-1)$, I_i^2 $(1 \leq I_i^2 \leq 2^{m_2}-1)$ and I_i^3 $(1 \leq I_i^3 \leq 2^{m_3}-1)$ are generated according to the weight of the packet, identification of the sensor and number of slots needed. The packet delay time is used here to determine the packet weight as

$$I_i^1 = \begin{cases} \lceil \chi_i(2^{m_1}-1)/\Delta \rceil & \text{if } \chi_i < \Delta \\ 2^{m_1}-1 & \text{if } \chi_i \geq \Delta \end{cases}, \tag{3}$$

where χ_i denotes the time between the generation of a packet and the current time and Δ is a preset threshold value. Then, packets with longer delays have higher priority when reserving the same time slots.

The coordinator will assign time slots to sensors after receiving the reservation information, all the requirements will be satisfied if the number of time slots is sufficient, and slots will be assigned to sensors with higher criterion weights when wireless resources are insufficient. The criterion weight is defined as

$$W_i = \frac{I_i^1}{I_i^3}. \tag{4}$$

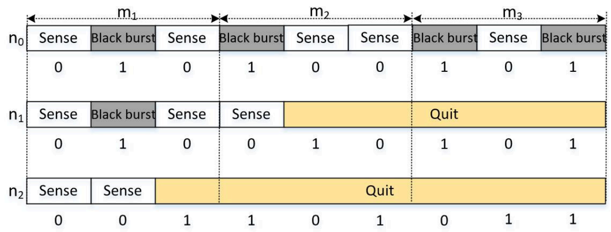

Fig. 3. Illustration of reservation.

Then, sensors who need fewer time slots will be arranged first if they have the same priority value.

C. Adaptive power control

In this section, an adaptive power control scheme is proposed for sensors to improve energy efficiency based on limited power resources. We use the packet reception rate to estimate the channel state and further adjust the transmission power based on the estimated channel state and energy constraints.

1) Energy model: During the EH period, $\mathcal{C}$ transmits a unit energy signal x_c using power p_c. Then, the signals received by sensor n_i can be expressed as

$$y_{ci} = h_{ci}\sqrt{p_c}x_c + \epsilon_i, \tag{5}$$

where h_{ci} represents the channel gain from $\mathcal{C}$ to n_i, and ϵ_i denotes the AWGN. The maximum energy that can be harvested by n_i during the j-th EH period is

$$E_{hi}^j = \delta p_c |h_{ci}|^2 T_e^j, \tag{6}$$

where $\delta \in (0, 1)$ is the energy conversion efficiency and T_e^j denotes the duration of the beacon period in the j-th superframe.

The harvested energy is mainly used by data uploading, data receiving and slot reservation. The energy used to receive the beacon broadcast by $\mathcal{C}$ during the j-th superframe is

$$E_{bi}^j = P_r \frac{L_b^j}{R}, \tag{7}$$

where P_r, L_b^j and R denote the power used to receive packets, length of the j-th beacon and transmission rate, respectively. The energy used to receive data during the AP is

$$E_{ai}^j = P_r \frac{L_a^j}{R}, \tag{8}$$

where L_b^j denotes arrangement data broadcast by $\mathcal{C}$. The energy used to upload one packet can be expressed by

$$E_{ui}^j = P_t^j \frac{L_i^j}{R}, \tag{9}$$

where P_t^j and L_i^j denote the power used to transmit packets and length of the packet uploaded by sensor n_i during the j-th superframe. The energy used when reserving slots is

$$E_{ri}^j = P_t^j t_{ri}, \tag{10}$$

where t_{ri} denotes time usd to broadcast black burst signal, respectively.

Super capacitors are used to store the harvested energy, and sensors use the stored energy to perform the transmission tasks. Let E^{max} denotes the maximum energy a supercapacitor can store, and let $\overleftarrow{E_{ei}^j}$ and $\overrightarrow{E_{ei}^j}$ denote the energy stored in the capacitor before and after the EH period; then,

$$\overleftarrow{E_{ei}^j} = \overrightarrow{E_{ei}^{j-1}} - E_{bi}^j - \psi_1 E_{ri}^j - \psi_2 E_{ai}^j - \psi_3 E_{ui}^{j-1} - E_{si}^{j-1}, \tag{11}$$

$$\overrightarrow{E_{ei}^j} = min\{\overleftarrow{E_{ei}^j} + E_{hi}^j, E^{max}\}. \tag{12}$$

where E_{si}^j denotes energy consumed during the sleep period, ψ_1, ψ_2 and ψ_3 denote whether sensor n_i needs to upload data, whether the reservation process is executed successfully and whether the data are uploaded, respectively.

2) Transmission power adjustment scheme: Because the harvested energy is constrained, optimizing the allocation of the transmission power plays an important role in improving the energy efficiency and the network performance. We adjust the transmission power based on the estimated channel state, and the packet reception rate is calculated first. After receiving packets uploaded by sensors, $\mathcal{C}$ does not send Acks back immediately during the upload period. A N bit value Flag is packed in the beacon frame corresponding to Acks for sensors, while the corresponding bit value b_i is set to one if $\mathcal{C}$ received information from sensor n_i during the last upload period. Assume sensor n_i has uploaded u packets using power p_{ij} and received r Acks; then, the packet reception rate can be estimated by

$$Pr_{n_i}(p_{ij}) = \frac{r}{u}. \tag{13}$$

The latest transmitted packets are used to calculate the packet reception rate, which can better reflect the current channel status. Sensors can adjust the transmission power according to the estimated channel state, and the adaptive scheduling scheme is given below.

Assume that the harvested energy that can be used to upload data is E_i, then the transmitting power value is constrained

$$p_{ij} \leq min\{\frac{E_i}{t_i}, P_{max}\} \tag{14}$$

where P_{max} denotes the maximum transmission power and t_i is the during of the data transmitting

$$t_i = \frac{L_i}{R}, \tag{15}$$

where L_i denotes the packet length and R is the transmitting rate. Consequently, the information that is received by $\mathcal{C}$ can be expressed as

$$y_{ic} = g_{ic}\sqrt{p_{ij}}x_i + \epsilon_c, \tag{16}$$

where g_{ic} represents the channel gain from n_i to $\mathcal{C}$, and ϵ_c denotes the AWGN.

The signal-to-noise ratio (SNR) at the coordinate node can be written as

$$\gamma_c = \frac{p_{ij}|g_{ic}|^2}{\sigma_c^2}, \tag{17}$$

where σ_c^2 is the power of the noise power of the noise signal at $\mathcal{C}$.

Higher transmission power is desired if the energy is sufficient because the packet loss rate increases with the deterioration in SNR. An optimal power can be chosen for nodes in traditional networks since a sufficient power supply can be guaranteed. However, energy must be harvested and stored for sensors in EH-powered WBANs, and fewer packets can be sent when higher transmission power is used. Therefore, the packet reception rate and the transmission frequency can all affect the throughput, both of which are influenced by the transmission power. The probability of successfully receiving a packet for noncoherent FSK is [45]

$$\begin{aligned} F(p_{ij}) &= (1-\frac{1}{2}exp^{-\frac{\alpha}{2}})^{L_b} \\ &= (1-\frac{1}{2}exp^{\beta})^{L_b}, \end{aligned} \tag{18}$$

where $\frac{1}{2}exp^{-\frac{\alpha}{2}}$ is the probability of bit error, $\alpha = \frac{\gamma_c B_N}{R}$, $\beta = -\frac{\alpha}{2} = -\frac{\gamma_c B_N}{2R}$, L_b and B_N denote the packet length in bits and the noise bandwidth, respectively.

Sensor n_i transmits a packet using power p_{ij}, and $\mathcal{C}$ can receive the packet with probability $F(p_{ij})$. Then, the energy efficiency can be expressed by

$$\begin{aligned} \Phi(p_{ij}) &= \frac{(1-\frac{1}{2}exp^{-\frac{\alpha}{2}})^{L_b}}{p_{ij}t_i} \\ &= -\frac{B_N|g_{ic}|^2}{2L_i\sigma_c^2\beta}(1-\frac{1}{2}exp^{\beta})^{L_b} \\ &= \frac{U}{\beta}(1-\frac{1}{2}exp^{\beta})^{L_b}, \end{aligned} \tag{19}$$

where $U = -\frac{B_N|g_{ic}|^2}{2L_i\sigma_c^2}$. To maximize the network throughput, the energy efficiency must be guaranteed first if harvested energy is insufficient, and improving the packet reception rate can be further considered if there is residual energy. To solve the maximize energy efficiency problem, we can take the derivative of $\Phi(p_{ij})$ and obtain

$$\begin{aligned} \Phi'(p_{ij}) &= [\frac{U}{\beta}(1-\frac{1}{2}exp^{\beta})]' \\ &= \frac{U(1-\frac{1}{2}exp^{\beta})^{L_b-1}}{2\beta^2}(exp^{\beta}-\beta L_b exp^{\beta}-2). \end{aligned} \tag{20}$$

To optimize the energy efficiency, one of the most important questions is whether a proper β exists that can maximize $\Phi(p_{ij})$. We have the following theorem to solve this problem.

Theorem 1. The equation $exp^{\beta}-\beta L_b exp^{\beta}-2=0$ has a solution $\beta^\star(\beta^\star < -1)$, and the optimized energy efficiency can be achieved when β equals to $\beta^\star$.

Proof. See Appendix.

The maximum value of $\Phi(p_{ij})$ can be obtained by solving the equation $\Phi'(p_{ij}) = 0$ as

$$exp^{\beta}-\beta L_b exp^{\beta}-2=0, \tag{21}$$

It is difficult to determine the accurate value of $\beta^\star$ because the computing resources of sensors are definitely limited. An approximate value can be calculated using algorithms such as Newton's method [46]. The value of $\beta^\star$ is used here to determine whether the transmission power adopted is desired and how to adjust the power value. The adjustment algorithm is given in Alg. 1.

Algorithm 1 Algorithm for transmission power adjustment

Initialize phase:

u and r denote the number of packets uploaded and the number of Acks received

β_{th} is the error range of β, p_Δ is the step size for power adjustments

N_{th} denotes a step value to trigger the adjustment

Calculate value $\beta^\star$ for uploaded packet

Adjustment phase:

while $\beta > \beta^\star$ or $\beta^\star - \beta > \beta_{th}$ **do**
  if a beacon is received **then**
    if an ack is contained **then**
      $r \leftarrow r+1$
    end if
    if $u == N_{th}$ **then**
      $p_r \leftarrow \frac{r}{u}$
      $\beta \leftarrow ln(2(1-p_r^{\frac{1}{L_b}}))$
      if $\beta > \beta^\star$ **then**
        $p_w \leftarrow p_w + p_\Delta$
      else if $\beta^\star - \beta > \beta_{th}$ **then**
        $p_w \leftarrow p_w - p_\Delta$
      end if
      $r \leftarrow 0$
      $u \leftarrow 0$
    end if
  end if
  if a packet is uploaded during the UP **then**
    $u \leftarrow u+1$
  end if
end while

According to Eq. 18, the value of β correlated with power p_{ij} can be obtained by

$$\beta = ln(2(1-F(p_{ij})^{\frac{1}{L_b}})), \tag{22}$$

where $F(p_{ij})$ is the packet reception rate, which is determined by the channel state. Although sensors do not know the accurate value of $F(p_{ij})$, an estimated value $Pr_{n_i}(p_{ij})$ can be used here to calculate the β value. Because $\beta = -\gamma_c B_N/2R$, a smaller p_{ij} results in a lower γ_c and higher β value. Then, the transmission power should be increased to guarantee the energy efficiency if $\beta > \beta^\star$. However, if $\beta < \beta^\star$ and the average energy that can be used to upload packets is larger than the energy used to transmit packets using power $P_i^\star$, sensor n_i can further increase the packet reception rate by using larger transmission power, as the energy efficiency can be guaranteed and more energy can be used.

D. Superframe adjustment

The coordinator is responsible for dynamically adjusting the length of each period in the superframe to improve the network performance. Whether a sensor can upload generated packets successfully is affected mainly by the available energy and wireless spectrum resources. Let T_b^j, T_e^j, T_r^j, T_a^j, T_u^j and T_s^j

denote the lengths of BP, EP, RP, AP, UP and SP during the j-th superframe; then,

$$\frac{1}{M} = T_b^j + T_e^j + T_r^j + T_a^j + T_u^j + T_s^j, \tag{23}$$

$$T_b^j = \frac{L_b^j}{R}, \tag{24}$$

$$T_a^j = \frac{L_a^j}{R}, \tag{25}$$

$$T_r^j = min\{QT_{ms} + T_{switch}, T_r^{max}\}, \tag{26}$$

where T_r^{max} is a preset upper limit to ensure that enough time can be used by energy harvesting and data uploading. Number Q is calculated according to the desired success rate ϱ and average packet upload number N_{upload}

$$Q = 1/(1 - \varrho^{\frac{1}{N_{upload}-1}}), Q \in \{Q_{min}, Q_{max}\}. \tag{27}$$

The value of Q will be set to the upper or lower limit value if it exceeds the bound.

Based on the sensors' average energy harvesting rate ν_i and packets' arrival rate λ_i, the desired EP length for n_i can be calculated by

$$T_{h_i} = \frac{\lambda_i \overline{E_i}}{\nu_i} = \frac{\lambda_i}{\nu_i}(\frac{P_i^* \overline{L_i}}{R} + \overline{E_i^{'}}), \tag{28}$$

where $\overline{E_i}$ denotes the average energy used to upload one packet using the desired transmission power, $\overline{L_i}$ denotes the average packet length generated by n_i, and $\overline{E_i^{'}}$ denotes the average energy used during other periods. Then, the desired EP length to meet all sensor requirements is $T_{h_i}^{max} = max\{T_{h_i}, i \in [1, N]\}$.

Based on the average number of slots used to upload packets $\overline{I_i^3}$ and packet arrival rate λ_i, the desired UP length can be calculated by

$$T_u^{max} = \sum_{i=1}^{N} \overline{I_i^3} \lambda_i. \tag{29}$$

Desired lengths can be assigned to EP and UP ($T_e^j = T_h^{max}$ and $T_u^j = T_u^{max}$) if $\frac{1}{M} \geq T_b^j + T_e^j + T_r^j + T_a^j + T_u^j$, and T_s^j can be calculated as $\frac{1}{M} - (T_b^j + T_e^j + T_r^j + T_a^j + T_u^j)$. Otherwise, wireless spectrum resources are insufficient, and the lengths of EP and UP are

$$\begin{cases} T_e^j = \eta T_\Omega, \\ T_u^j = (1-\eta) T_\Omega, \end{cases}, \tag{30}$$

where $T_\Omega = 1/M - (T_b^j + T_r^j + T_a^j)$. The packet uploading process is affected by the assailable energy and wireless spectrum simultaneously, and the number of packets that can be uploaded is

$$K = min\{\sum_{i=1}^{N} \eta T_\Omega / T_{h_i}^{'}, N(1-\eta)T_\Omega / T_u^{max}\}, \tag{31}$$

where

$$T_{h_i}^{'} = \begin{cases} T_{h_i} & \text{if } T_{h_i} > \eta T_\Omega \\ \eta T_\Omega & \text{otherwise.} \end{cases}, \tag{32}$$

Harvested energy or usable time slots will be insufficient if η is too small or too large, the proper value can be calculated by $\sum_{i=1}^{N} \eta T_\Omega / T_{h_i}^{'} = N(1-\eta)T_\Omega / T_u^{max}$, and then

$$\eta = \frac{N \sum_{i=1}^{N} T_{h_i}^{'}}{\sum_{i=1}^{N} T_{h_i}^{'} + T_u^{max}}. \tag{33}$$

The lengths of EP and UP will be ηT_Ω and $(1-\eta)T_\Omega$ in a dense network, and the length of SP equals 0 at this time.

V. SIMULATION RESULTS

TABLE I
SIMULATION PARAMETER

Parameter	Value
M	10
N	$10 \sim 60$
δ	0.8
$PL(d_0)$	55
d_0	$1m$
n	2.4
R	$250kbps$
m_1, m_2, m_3	$3, 6, 3$
$Mini\ Slot + Radio\ Switch$	$5\mu s + 1\mu s$
Q_{min}, Q_{max}	$10, 200$
λ	0.8
Δ	$200ms$
$Simulation\ Time$	$1hour$

To evaluate the proposed scheme, we conducted a series of simulations in OMNeT++ and present the results in this section. A one-hop star network that contains one coordinator and N sensors is considered, while sensors harvest RF energy from the coordinator to serve as self-sustainable power. The transmission power of the coordinator is set to 0.5 mW. Channel gains are modeled as $h_{ci} = g_{ic} = \sqrt{10^{-PL(d)}}$ [26]. The maximum length of the payload is 127 bytes, and the transmission rate is 250 kbps [35]. To enable the operation, the chip must consume an average power less than the power harvested [47]. The average power consumed during the active state, idle state and sleep state can be lower to 1.02 μW [48], 470 nW [49] and 5.2 nW [50] for wearable sensors to save energy and improve lifetime. During the simulation, Rx power of sensors is set to be 1.5 μW and power consumed during the idle and sleep state are 0.1 μW and 0.05 μW. Table I summarizes the main parameters used in the simulations. Each second is divided into ten superframes (M=10), and the length of each superframe equals 100 ms. Each evaluation is performed 10 times and the average result of the simulations is presented.

As in the analysis, the performance of the proposed protocol is compared with ATMAC [51], to show the effect of applying the transmission power adjustment algorithm and the superframe adjustment scheme, both fixed EH period (PA) and dynamically adjusted EH period (PASA) are considered in the simulation. Length of the EH period for PA scheme and ATMAC is set to be 20 ms (PA-20, ATMAC-20) or 40 ms

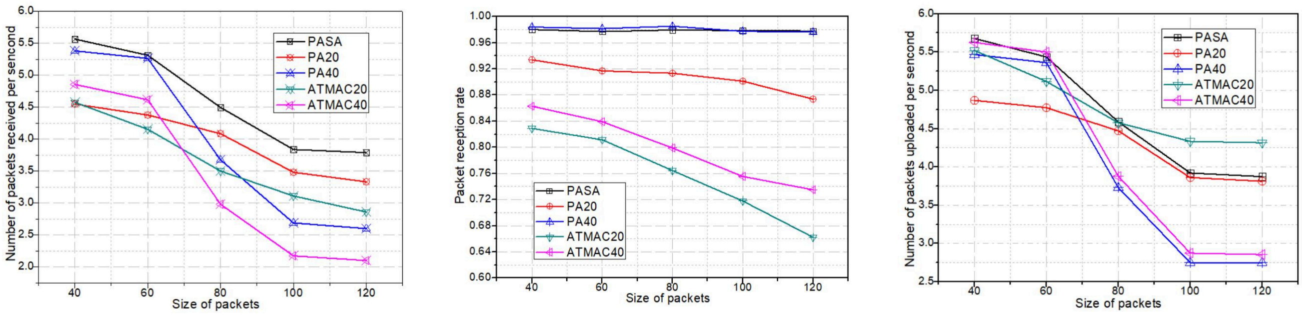

Fig. 4. Performances under different packet sizes.

(PA-40, ATMAC-40). The throughput of the network (average number of packets received by the coordinator per sensor per second), packet reception rate, and transmission frequency (average number of packets transmitted by one sensor per second) are used as the performance metrics to evaluate the protocols.

We first evaluated the performance of the schemes under different packet sizes. The size of the packets generated by the sensors is in the range of 40 bytes to 120 bytes. The number of sensors is 40, and the packet generation rate is 0.8. Fig. 4. shows the simulation results. With the increase in the packet size, each sensor needs more energy and wireless channel resources to upload one packet. Fig. 4(a) shows the network throughput. Time slots are sufficient when the size of the data packets is small for both the PA scheme and ATMAC, higher network throughput can be gained for schemes with longer EH period length since more energy can be harvested, but the throughput drops faster for these schemes with the increase of the packet size since sensors cannot gain enough time slots to upload packets even if the energy is sufficient. ATMAC has the lowest network throughput because only the time slot management scheme is considered, and the probability that packets can be received correctly by the coordinator will be lower as sensors do not estimate the channel state and adjust the transmission power accordingly. Better performance can be gained for the PASA scheme since the coordinator adjusts the superframe according to sensor uploading requirements; only when the EH efficiency and the channel resource demand are considered coordinately can the network performance be optimized in the EH-based WBAN.

Fig. 4(b) shows the packet reception rate. Because packets cannot be uploaded as soon as they are generated due to the constraints of available energy and time slots, the total number of packets uploaded by sensors is diverse when different protocols are applied to the network. Our proposed protocol outperforms ATMAC, and a higher packet reception rate can be gained since each sensor adjusts the transmission power according to the channel states and uploads packets using power not less than $P_i^\star$. A higher packet reception rate can be gained in PA-40 compared with PA-20 when the size of the packets is small since more energy can be harvested and available time slots are sufficient. Although the available time slots are insufficient which results in lower throughput in PA-40 when the size of the packets is large, sensors can still harvest more energy in PA-40 to ensure a high reception rate. Because no power adjustment scheme is deployed in ATMAC, part of the energy will be wasted when sensors upload packets using high power, and packets will be lost when low power is adopted, thus, ATMAC-40 has a lower packet reception rate compared with PA-20 even though sensors can harvest more energy.

Fig. 4(c) shows the average transmission frequency. Compare with ATMAC, fewer packets are transmitted in our protocol to guarantee energy efficiency since energy will be wasted if the transmission power is too low and the coordinator cannot receive the packets successfully. For protocols with a fixed EH period length, more packets can be transmitted when the size of packets is small if the length of the EH period is 40 ms since time slots are sufficient and harvested energy is higher to support data uploading. But time slots will be insufficient when the size of packets is large, and fewer packets can be transmitted compared with protocols whose EH period is 20 ms then.

We also explored how the network is impacted by varying network densities. Sensors are randomly placed within 10 to 60 cm from the coordinator, and the size of the generated packets ranges from 20 to 100 bytes. The number of sensors in the network is set from 10 to 60. Once a sensor attempts to upload a packet, whether the packet can be uploaded successfully is affected by both available energy and usable time slots, while available energy is the main constraint in a sparse network, and the impact of available time slots will be greater with increasing network density. Fig. 5. shows the simulation results. Sensors can harvest more energy in PA-40 and ATMAC-40 compared with PA-20 and ATMAC-20, and more packets can be uploaded successfully in a sparse network. But sensors have to wait for available time slots before uploading packets, and the average throughput will be under downward pressure in a dense network, then, PA-20 and ATMAC-20 have better performance in a dense network since more time slots are available. Sensors adjust transmission power in PA scheme, and higher throughput can be gained compared with ATMAC. Constraints based on both available energy and available time slots simultaneously show that the average throughput will be higher when the EH period is prolonged when the number of sensors is small and shorten the EH period in dense networks. PASA scheme has the highest throughput because sensors adjust transmission power according to the estimated channel state and choose the proper power to upload packets, while the division of the superframe

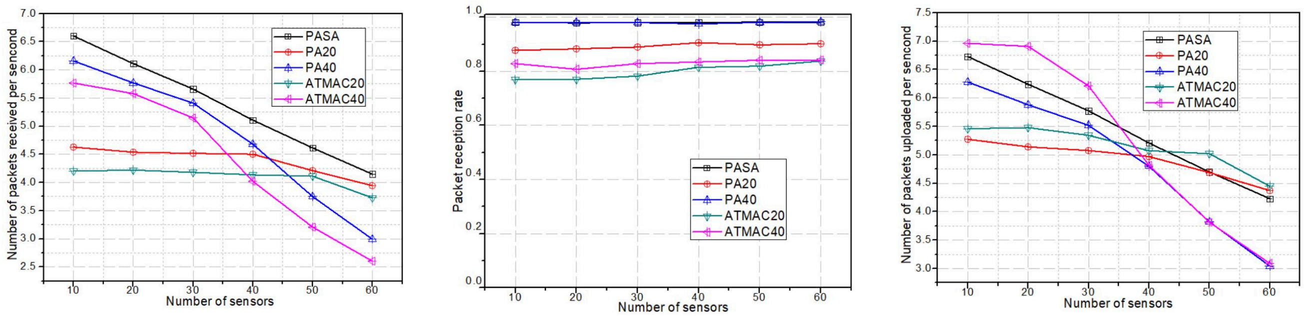

Fig. 5. Performances under different network densities.

can be adjusted by the coordinator in dense networks to ensure that more time slots can be used to upload packets.

Fig. 5(b) shows the packet reception rate, which is mainly affected by the transmission power. A high packet reception rate can be achieved in PASA since sensors can choose the proper transmission power to upload packets. For both PA scheme and ATMAC, more nodes need to allocate time slots to upload data with the increasement of the network density. Sensors have to wait longer before acquiring time slots, while more energy can be harvested and stored during this time. Then, sensors can upload packets using higher transmission power when time slots are assigned, which results in a higher packet reception rate.

The transmission frequency still drops faster with the increase of the network density when the length of the EH period is 40 ms, as shown in Fig. 5(c). A lower delay can be gained in ATMAC since sensors upload packets more frequently without considering the energy constraint. For RF-based EH WBANs, energy and wireless resources are strictly constrained compared with other kinds of networks, higher throughput and lower delay cannot be achieved simultaneously. Appropriately reducing the transmission frequency is needed to guarantee the packet reception rate and further improve the network throughput.

VI. Conclusion

In this paper, we propose a hybrid MAC protocol to enable adaptive scheduling RF energy harvesting-powered WBANs. A dynamic transmission power optimization scheme is proposed for sensors to improve energy efficiency and network performance. The superframe structure is redesigned to enable the proposed hybrid protocol, and the lengths of the periods in the superframe are adjusted by the coordinator according to the sensor requirements. Simulation results verify that the proposed hybrid MAC protocol can effectively improve network adaptability and performance.

In the future, we will extend this work with a cooperation approach, where we plan to reduce the amount of energy transmission on the basis of ensuring the network transmission performance by cooperating between sensors. Sensors located near the coordinator will work as relay nodes because more energy can be harvested compared with further sensors. A cooperative relay mechanism and sleep adjustment scheme based on the overall arrangement of the coordinator will be considered.

Appendix

Proof. Value of $\beta \in (-\infty, 0]$ since $\beta = -\frac{\gamma_c B_N}{2R}$. Because L_b is the length of a packet which is obviously bigger than 96 bits (the sum of the lengths of SHR, PHR and MFR is 12 bytes), the probability that a packet can be successfully received is $(1-\frac{1}{2}exp^{\beta})^{L_b} < (1-\frac{1}{2}exp^{-1})^{96} \approx 3.35 * 10^{-9}$ when $\beta > -1$, which is too low to accept. Thus, the value of β should be in range $(-\infty, -1)$.

Based on equation $exp^{\beta} - \beta L_b exp^{\beta} - 2 = 0$, we can get $\frac{1}{2} - \frac{L_b}{2}\beta = exp^{-\beta}$. The solutions of the equation are the focus of the line $y = \frac{1}{2} - \frac{L_b}{2}\beta$ and the power function $y = exp^{-\beta}$. and there are at most two solutions.

For equation $f(\beta) = exp^{\beta} - \beta L_b exp^{\beta} - 2$, when $\beta \to -\infty$,

$$\lim_{\beta \to -\infty} exp^{\beta} = 0$$

$$\lim_{\beta \to -\infty} \beta exp^{\beta} = \lim_{\beta \to -\infty} \frac{1}{-\frac{exp^{\beta}}{(exp^{\beta})^2}} = \lim_{\beta \to -\infty} -exp^{\beta} = 0$$

Thus,

$$\lim_{\beta \to -\infty} f(\beta) = \lim_{\beta \to -\infty} exp^{\beta} - \lim_{\beta \to -\infty} \beta L_b exp^{\beta} - 2 = -2 < 0$$

.

Meanwhile, $f(0) = -1 < 0$ and $f(-1) = exp^{-1} + L_b exp^{-1} - 2 = \frac{1+L_b}{exp} - 2 > \frac{97}{exp} - 2 > 0$. Thus, we can get a solution of the equation $exp^{\beta} - \beta L_b exp^{\beta} - 2 = 0$ which are $\beta^{\star}$ in the range $(-\infty, -1)$. The value of $f(\beta) < 0$ when $\beta \in (-\infty, \beta^{\star})$, and $f(\beta) > 0$ when $\beta \in (\beta^{\star}, -1)$. For Eq. 20, $\frac{(1-\frac{1}{2}exp^{\beta})^{L_b-1}}{2\beta^2} > 0$ and $U = -\frac{B_N |g_{ic}|^2}{2L_i \sigma_c^2} < 0$, then, $\Phi'(p_{ij}) > 0$ when $\beta < \beta^{\star}$ and $\Phi'(p_{ij}) < 0$ when $\beta \in (\beta^{\star}, -1)$, a maximum value can be achieved for $\Phi(p_{ij})$ when $\beta = \beta^{\star}$. Therefore, The equation $exp^{\beta} - \beta L_b exp^{\beta} - 2 = 0$ has a solution $\beta^{\star}(\beta^{\star} < -1)$, and the optimized energy efficiency can be achieved when β equals to $\beta^{\star}$.

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Juncheng Hu received the B.E. degree from the College of Computer Science, Jilin University, China, in 2017, where he is currently pursuing the Ph.D. degree. His research interest includes wireless body area networks, network protocol, and feature selection.

Gaochao Xu received the B.S., M.S., and Ph.D. degrees from the College of Computer Science and Technology, Jilin University, China, in 1988, 1991, and 1995,respectively. He is currently a Professor and a Ph.D. Supervisor with the College of Computer Science and Technology, Jilin University. His main research interests included Machine learning, the Internet of Things, information security, software testing, and software reliability assessment. As a person-in-charge or a principal participant, he has finished more than 10 national, provincial, and ministerial level research projects of China.

Liang Hu was born in 1968. He received the B.S. degree from the Harbin Institute of Technology (HIT), Harbin, and the M.S. and Ph.D. degrees from the College of Computer Science and Technology, Jilin University (JLU), Changchun, China. He has been a Professor, since 2002 and has been a Ph.D. supervisor, since 2003 with the School of Jilin University. His current research interests include distributed computing, network computing and security, wireless network, and so on.

Shujing Li received the B.S., M.S., and Ph.D. degrees from the College of Computer Science and Technology, Jilin University, China, in 2008, 2011, and 2020, respectively. He is doing post-doctoral research in the College of mathematics in Jilin University.

He worked as an Assistant Engineer with the Jiangsu Institute of Automation, Lianyungang, China, from 2011 to 2012, and then worked as an Engineer from 2013 to 2017. He is interested in topics related to WBAN and VANET, especially for MAC layer protocols, and cross-layer optimization.

Yang Xing received his Ph. D. degree from Cranfield University, UK, in 2018. He is currently a Lecture with Cranfield University. Before joining Cranfield, he was a Research Associate with the Department of Computer Science, University of Oxford, UK, from 2020 to 2021, and a Research Fellow with the School Mechanical and Aerospace Engineering, Nanyang Technological University, Singapore, from 2019 to 2020. His research interests include machine learning, human behavior modeling and personal area network. He received the IV2018 Best Workshop/Special Issue Paper Award. Dr. Xing serves as a Guest Editor for IEEE IoT, IEEE ITSM, and Frontiers in Mechanical Engineering. He is also an active reviewer for IEEE ITS, TVT, TIE, and IEEE/ASME Transactions on Mechatronics, etc.

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Hu, Juncheng

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