QoS-Driven Scheduling Approach Using Optimal Slot Allocation for Wireless Body Area Networks

Zhisheng Yan and Bin Liu
School of Information Science and Technology
University of Science and Technology of China
Hefei, Anhui, 230027, P. R. China
Email: zsyan@mail.ustc.edu.cn, flowice@ustc.edu.cn

Chang Wen Chen
Computer Science and Engineering Department
University at Buffalo, the State University of New York
Buffalo, NY, 14260-2000 USA
Email: chencw@buffalo.edu

***Abstract*—Wireless Body Area Network (WBAN) is a promising type of networks that mainly targets at applications in ubiquitous communication and e-Health services. Different from other types of networks, one important challenge for WBAN is that its quality of service (QoS) requirement, in terms of delivery probability and data rate, will be time varying since human body is a highly dynamic physical environment. Another significant challenge for WBAN is that energy efficiency needs to be guaranteed in such a resource-limited network. In this paper, a QoS-driven scheduling approach is proposed to address these challenges. We model the WBAN channel as a Markov model as suggested by the emerging IEEE 802.15.6 BAN standard and propose a threshold-based scheme to adjust the transmission order of nodes. The number of slots for each node is optimally assigned according to the QoS requirement while minimizing the energy consumption of nodes. The results from extensive simulations show that the proposed approach can provide high QoS and energy efficiency under different network conditions, especially in highly heterogeneous ones in WBAN.**

I. Introduction

With the development of miniaturized, high-performance, and low-power sensor nodes, and the recent advances in wireless networking technologies, communication in or around human body using wireless body area networks (WBAN) has become practically feasible. Healthcare community and engineering industry have shown increased interests in WBAN, since this emerging system provides efficiency to healthcare related services, such as health monitoring, medical care and emergency management. WBAN is a body-centric system that consists of two categories of nodes: in-body, on-body or around-body sensor nodes, and personal server (PS) equipped on human body. These nodes usually form a star topology network with single-hop communication. Sensor nodes collect various kinds of information in or around human body and transmit them to the PS for further processing.

The healthcare oriented applications of WBAN raise the special requirements of quality of service (QoS), including data rate, delivery probability, and latency. Sensor nodes with different functionalities, such as heart-rate, electroencephalogram (EEG), and video, require the data rate changing from a few kbps up to 10Mbps [1]. Such WBAN system requests the support of periodic, real-time and emergency traffic. Furthermore, the reliability of WBAN needs to be guaranteed against the lossy WBAN channel caused by energy absorption, body movement, and multipath due to surrounding environment [2]. Channel measurements have shown that deep fading of on-body channel can last 10-400ms which is much longer than traditional wireless networks [3]. Another important issue in WBAN is energy efficiency since it is necessary for batteries of sensor nodes to work unobtrusively for months or even years. Hence, designing an appropriate scheduling strategy for WBAN becomes imperative in order to combat the aforementioned adversaries.

The primary concern of existing WBAN scheduling approaches [4]–[7] is energy efficiency rather than QoS. In [6], for example, proper length of beacon interval and synchronization scheme using guard duration are adopted to enhance energy efficiency. However, they only provide limited support for QoS, such as one alert slot for emergency [4] or extra reserved slots for retransmission assuming constant packet loss [5]. More importantly, the particular traffic and channel characteristics of WBAN have not yet been well exploited. Specifically, the scheduling approaches using fixed slot allocation [4]–[7] cannot meet WBAN traffic demands that are usually dynamic and dictated by the time-varying conditions of human body and environment. Moreover, time-varying deep fading in WBAN may cause large packet loss and energy wastage in fixed allocation approach as in [4]–[7]. Tselishchev *et al.* [8] proposed a variable TDMA-based scheduling approach called Flipping to reduce losses in WBAN. The transmission order of a node in a TDMA period, known as *superframe*, is postponed or moved ahead in order to increases the node average delivery probability based on channel information in previous superframe. However, only one slot is allowed to be assigned to a node, which may not satisfy traffic demands of nodes with relatively high data rate. The scheduling approach is aimed at reducing average node packet loss and hence certain high priority nodes may still suffer intolerant packet loss. We have recently developed a hybrid contention and TDMA MAC protocol to handle channel fading in WBAN [9]. The contention period is used to interleave the packets from nodes/links. Thus when a node regains its transmission chance after a transmission failure and subsequent random backoff, the channel condition may improve and so retransmission may be successful. However, the channel utilization and energy efficiency is negatively impacted due to introduction

978-1-4577-2040-6/12/$26.00 ©2012 IEEE

of contention-based period. Besides, mitigating the impact of fading only by utilizing the nature of contention to timely spread the transmissions is inadequate. It is more appropriate to design a scheduling strategy with the consideration of the special WBAN channel model so as to increase reliability.

In this paper, we consider the characteristics and models of WBAN and propose a novel TDMA-based scheduling approach that concurrently meets the requirements of energy efficiency and QoS provisioning in star-topology WBAN. Specifically, we model the WBAN channel dynamics as a Markov process, as suggested by IEEE 802.15.6 BAN task group [3]. With this way, we are able to estimate the condition of a link based on its condition of most recent history, i.e., most recent transmission outcome for the link. We design a threshold-based scheme to adjust the transmission order of sensor nodes using channel estimation, which enables each node to transmit in slots with relatively good condition (relatively low packet loss rate) and to satisfy the requirement of delivery probability as much as possible. The number of allocated slots for each node is determined according to both energy and QoS demands. Accordingly, we formulate an optimization problem that optimizes the number of slots allocated to each node while taking the constraints of varying data rate and delivery probability of WBAN into considerations. The objective of the proposed problem is to minimize the total transmissions, or equivalently total energy consumptions, of WBAN. The major contribution of this paper is to explore the characteristics and modeling of WBAN such as dynamic and heterogeneous traffic and channel status, and to develop an energy-efficient scheduling approach that guarantees the QoS in terms of data rate and delivery probability.

The rest of this paper is organized as follows. In Section II, we describe the system model in detail. The QoS-driven scheduling approach is introduced in section III. We then evaluate the performance of proposed scheduling approach and present the results in Section IV. Finally we conclude this paper in Section V.

II. System Model

We consider a typical star-topology WBAN that consists of multiple on-body sensor nodes and one on-body PS. We assume that $\mathcal{W}$ is the set of sensor nodes in WBAN and each node is represented by its index $i, i = 1, 2 \cdots N$. Since WBAN covers a relatively short range, we assume sensor nodes directly transmit collected data to the PS without relaying. As strongly recommended by IEEE 802.15.6 BAN task group [10], we adopt a TDMA-based scheduling approach in WBAN to avoid collisions and to reduce energy wastage. The time axis is divided into periodic superframe period with constant length T. The superframe consists of continuous slots, during each of which one packet transmission (including data transmission, ACK reception, and radio transition time) from one node can be completed. At the beginning of each superframe, the PS computes the slot allocation based on QoS requirement and most recent channel history and broadcasts such information to sensor nodes through beacon packets. We assume sensor nodes are synchronized through beacon packets and are aware of slot boundaries. Node i then can periodically obtain the slot allocation, i.e., transmission order and number of assigned slots, and transmit data within the scheduled slots. They go to sleep during the slots scheduled for others to save energy and to avoid collisions. Since the beacon part and the transition time between sleep and active mode are much smaller than the time of data transmission, they are disregarded for simplicity of presentation. We also disregard the energy consumption from sleeping and only consider energy consumption when sensor nodes transmit and receive packets. However, it is easy to extend our model to accommodate beacon, transition time, and sleep energy.

Packet loss is introduced by various reasons, such as low received signal power and collisions. Sensor nodes in WBAN may suffer severe packet loss due to frequent body movements and variations in surrounding environment. IEEE 802.15.6 BAN task group has recommended a Markov model as one of WBAN channel models based on empirical measurements [3]. It has been shown that the Markov model characterizes the wireless dynamics in WBAN effectively [3]. In this paper, we model the wireless channel at each link (between each sensor node and the PS) as a two-state Markov process, where either "good" or "bad" state is allowed. Packets can be successfully transmitted in good state whereas in bad state packet transmissions would fail, which corresponds to the popular Gilbert link model [11]. However, it is important to note that our model can be extended to general Markov model with more than two states.

We denote the Markov transition probability matrix as $\mathbf{P}$,

$$\mathbf{P} = \begin{bmatrix} 1 - P_{BG} & P_{BG} \\ P_{GB} & 1 - P_{GB} \end{bmatrix} \tag{1}$$

where P_{GB} is the transition probability from a good state to a bad state, which represents the probability of a node's transmission failure in current slot given that it has succeeded in previous slot, and P_{BG} is the transition probability from a bad state to a good state. Notice that each link may have different transition probability matrix due to heterogeneous location and movement of sensor nodes. We denote the state of a link in certain slot is $X(0)$, which is either bad state (0) or good state (1). Then its probability of being in good state after τ slots is given by [8]

$$\begin{aligned} p(\tau) &= \begin{bmatrix} 1 - X(0) & X(0) \end{bmatrix} \cdot (\mathbf{P})^{\tau} \cdot \begin{bmatrix} 0 \\ 1 \end{bmatrix} \\ &= \begin{cases} \frac{P_{BG}}{Q} - \frac{P_{BG}(1-Q)^{\tau}}{Q} & X(0) = 0 \\ \frac{P_{BG}}{Q} + \frac{P_{GB}(1-Q)^{\tau}}{Q} & X(0) = 1 \end{cases} \end{aligned} \tag{2}$$

where $Q = P_{BG} + P_{GB}$. It is important to note that $p(\tau)$ is either monotonically increasing or decreasing as $X(0)$ equals to 0 or 1, respectively. When τ goes to infinity, $p(\tau)$ tends to $\frac{P_{BG}}{Q} = \frac{P_{BG}}{P_{BG}+P_{GB}}$, which refers as the long-term fraction of good slots, i.e., the long-term delivery probability. It should be emphasized that with a larger Q, the channel would vary from bad state to good state or from good state to bad state faster since $(1-Q)^{\tau}/Q$ is monotonically decreasing as Q increases.

III. Proposed QoS-Driven Scheduling Approach

In this section, we propose a novel scheduling approach that optimizes the slot allocation in superframe in order to address the challenges in QoS and energy efficiency in WBAN. Since real-time channel information is not available to the PS due to the periodic sleeping nature of sensor nodes, we aim at estimating channel conditions and scheduling slots to the node that can transmit packets with relatively high delivery probability. Based on the analysis of transmission reliability, we first derive the constraints of delivery probability and propose a threshold-based scheme to adjust the transmission order of nodes. Then the constraint of data rate is presented based on the traffic characteristic of WBAN. Finally we formulate an optimization problem to find the optimal number of slots assigned to each node while minimizing the energy consumption of sensor nodes.

A. Reliability Analysis and Threshold-based Adjustment of Transmission Order

In WBAN, the PS is only able to obtain outdated channel information when nodes transmit packets in their allocated slots and to distribute slot allocation at the beginning of a superframe. Hence, the most recent channel condition available to the PS, i.e., the outcome of the last allocated transmission in the previous superframe, for each node, is recognized as initial channel condition to estimate nodes' channel condition for the upcoming superframe. Those nodes whose initial channel condition is good or bad are denoted by the set $GOOD = \{i|X_i(0) = 1\}$ and by the set $BAD = \{i|X_i(0) = 0\}$, respectively. From the monotonicity of $p(\tau)$, we can find that the delivery probability will decrease with respect to time for nodes in the set $GOOD$, and increase with respect to time for nodes in the set BAD. It also means that initially successful nodes would have a higher delivery probability in the upcoming superframe if they transmit sooner and initially failed nodes would have lower delivery probability. Accordingly, we schedule those nodes initially known in good state ($i \in GOOD$) in the former part of superframe before the sensor nodes initially known in bad state ($i \in BAD$). Since nodes in WBAN may have different QoS requirements and channel conditions, the transmission order within each set also needs to be deliberately adjusted.

The requirement of delivery probability in WBAN may change according to varying context of human body and environment. To guarantee a reliable transmission, the delivery probability for the node i in its allocated slots should be no less than the threshold TH_i. For node i initially known in good state ($i \in GOOD$), if the transmission during its last allocated slot in the upcoming superframe can satisfy the threshold TH_i, transmissions during its other allocated slots can also meet the requirement due to the monotonically decreasing property of its delivery probability. Accordingly, the constraint of delivery probability of node i, $i \in GOOD$, is given by

$$p(D_i + x_i) \geq TH_i \Rightarrow x_i \leq a_i \tag{3}$$

where D_i is the number of slots have passed since node i finished its scheduled transmissions in the previous superframe, x_i is the index of the last allocated slot of node i in the upcoming superframe, and a_i is the upper bound of the index for the last allocated slot of node i in the upcoming superframe. In other words, all the slots for node i, $i \in GOOD$, should be scheduled before the a_ith slot of the upcoming superframe. Similarly, the corresponding constraint of delivery probability of node i, $i \in BAD$, is given by

$$p(D_i + y_i) \geq TH_i \Rightarrow y_i \geq b_i \tag{4}$$

where y_i is the index of the first allocated slot of node i in the upcoming superframe, and b_i is the lower bound of the index for the first allocated slot of node i in the upcoming superframe. It means that all the slots for node i should be scheduled after the b_ith slot of the upcoming superframe.

Based on the above analysis, we propose a threshold-based scheme to adjust the order within two sets, $GOOD$ and BAD. At the beginning of a superframe, the PS first computes all a_i's for node i belonging to the set $GOOD$ and all b_i's for node i belonging to the set BAD based on the available channel information and the slot allocation of previous superframe. The order of nodes within two sets is decided basically according to the value of a and b, respectively, i.e., a node with higher a is scheduled after a node with lower a within the set $GOOD$ and a node with higher b is scheduled after a node with lower b within the set BAD. However, there are some exceptions. For node $i \in GOOD$, if $\frac{P_{BGi}}{Q_i} \geq TH_i$, the delivery probability is always no less than TH_i. This means that node i can be scheduled in any position in the superframe to satisfy the threshold. We schedule such nodes at the latter part within the set $GOOD$ and the order among them is set based on the value of $\frac{P_{BGi}}{Q_i} - TH_i$. It is also important to note that the value of a_i may be negative, which means the delivery probability for such nodes has been below the threshold during the previous superframe. Thus the scheduling is only aiming at reducing the gap between actual delivery probability and the threshold by moving them ahead as much as possible. For node $i \in BAD$, there are also a case (when b_i is larger than T) that cannot meet the threshold. Then, the aim of scheduling is to reduce the gap between delivery probability and threshold. Therefore, we postpone such nodes at the end part of the superframe and the order among them is set according to the value of the gap between delivery probability and threshold.

B. Optimization of The Number of Allocated Slots

After deriving the reliability constraints, we now consider the constraint of data rate for each node. Sensor nodes normally send data to the PS in their assigned slots using a standard manner. As long as a sensor node completes its data transmission in the assigned slots or there is no available data packet in the sensor's buffer, it must go to sleep to save energy. All sensor nodes wake up at the beginning of a new superframe, for the purpose of updating slot allocation. If the slot allocation is changed, it indicates that the PS has detected the change in QoS requirement by data processing and analysis within the previous superframe. This QoS requirement lasts until the PS broadcasts another beacon packet requesting the system to change the slot allocation. Accordingly, the number of scheduled slots of each type of sensor nodes should be dynamically changed to satisfy the traffic requirement. The corresponding constraint of data rate for node i is given by

$$Rn_i \geq S_i T \tag{5}$$

where n_i and S_i are the number of allocated slots and the minimum data rate requirement of node i, respectively, and R is the transmission rate in WBAN radio.

In order to guarantee QoS provisioning for WBAN, we formulate an optimization problem to find the optimal transmission time, i.e., the number of allocated slots, of each node. It is crucial for WBAN to provide long-term services with sufficient energy supply. Sensor nodes are power-hungry whereas the PS is not and may be easy to recharge. Hence, the objective of the optimization is to minimize the sum of energy consumptions of all the sensor nodes with respect to the number of allocated slots of each node, subject to the constraints of traffic and reliability. Because only the energy consumption during data communications is considered in this research, the objective is equivalent to minimizing the total number of allocated slots in the system. The reliability constraint of WBAN has been given in (3-4). Here we convert them into the expressions in the form using the number of allocated slots n_i. According to (3), for node i initially known in good state ($i \in GOOD$), the number of its allocated slots and the slots scheduled before it should be no larger than a_i in order to fulfill the delivery probability threshold. Thus the reliability constraint for node i, $i \in GOOD$, can be also written as

$$n_i + \sum_{\{j|a_j<a_i\}} n_j \leq a_i \tag{6}$$

Similarly, the reliability constraint for node i, $i \in BAD$, can be converted as

$$\sum_{\{g|a_g \leq a_{\max}\}} n_g + \sum_{\{j|b_j<b_i\}} n_j \geq b_i \tag{7}$$

where $a_{\max} = \max\{a_i | i \in GOOD\}$. The optimization problem will then be formulated as follows.

$$\begin{array}{lll} \min_{(\mathbf{n})} & \sum_{i\in\mathcal{W}} n_i & \\ \text{s. t.} & Rn_i \geq S_i T & \forall i \in \mathcal{W} \\ & n_i + \sum_{\{j|a_j<a_i\}} n_j \leq a_i & i \in GOOD \\ & \sum_{\{g|a_g\leq a_{\max}\}} n_g + \sum_{\{j|b_j<b_i\}} n_j \geq b_i & i \in BAD \\ & \sum_{i\in\mathcal{W}} n_i \leq T & \forall i \in \mathcal{W} \end{array} \tag{8}$$

where $\mathbf{n}$ is the vector of number of allocated slots. The first constraint requires that the transmitted data should be no less than the minimum application-level request. The second and third constraint is the reliability constraint for initially good and bad nodes, respectively, which ensures their delivery probability is no less than a given threshold. The last constraint requires that the total number of the allocated slots should be no larger than the length of superframe. Since the objective function and the constraints are all linear, and the integer number of scheduled slots is desirable, the resulting optimization is an Integer Linear Programming (ILP) problem, which can be solved efficiently [12].

IV. Simulations and Performance Evaluations

In this section, we evaluate the performance of the QoS-driven scheduling approach using optimal slot allocation (denoted by *QoSOSA*) in terms of reliability and energy efficiency through simulations. We also compare the performance of the proposed approach with existing scheduling approach CA-MAC [9] that has been introduced in Section I and has shown certain level of QoS provisioning.

We deploy 5 sensor nodes and one PS in the WBAN, which is a typical setting of medical WBAN [1]. Since IEEE 802.15.6 BAN standard has not been finalized, we use one of the IEEE BAN radio proposals [13] as the physical radio model. The wireless transceivers operate in 2.4 GHz band with transmission rate of 1024kbps and the receiver sensitivity is -86dBm. We assume the slot duration is 10ms. Since we model each link between a node and the PS as a two-state Markov chain, it is important to configure appropriate Markov parameters to model the time-varying fading channel in WBAN. Instead of using transition probability, we use the value of $\frac{P_{BG}}{Q}$ and Q to describe the features of the channel since they have realistic signature, i.e., the long-term delivery probability and how fast the channel transits between states, respectively. From the public data set for the empirical channel measurements of WBAN [14], $\frac{P_{BG}}{Q}$ usually lies between 0.90 and 0.99 and Q lies between 0.05 and 0.5 [8]. The data rate and delivery probability requirement of sensor nodes are set according to their applications. The minimum data rate requirements for the 5 sensor nodes are set to be 81.92kbps, 81.92kbps, 163.84kbps, 163.84kbps, and 327.68kbps, respectively. The delivery probability thresholds of 5 sensor nodes are set to be 90%, 90%, 95%, 95%, and 95%, respectively. The length of the superframe is set to be 125ms if not specified particularly. Such duration is compatible to the default delay requirement of medical application (125ms) suggested by IEEE 802.15.6 BAN group [1]. The default values of current draw in the WBAN are specified according to MICAz mote [15]. We adopt an existing optimization toolbox YALMIP [16] to find the optimal solution of (8). When simulating CA-MAC, the same parameters indicated above are used except for those design-specific parameters. The parameters used in CA-MAC are set to the typical values in [9]. Each evaluation runs 16 times and each time we randomly choose $\frac{P_{BG}}{Q}$ and Q for each node from the two mentioned ranges, respectively, in order to cover a serial of practical channel status. Each simulation runs for 10000 periods of superframe. The simulation results described below are averaged over all the 16 scenarios.

A. Reliability

We compare the reliability performance of the proposed approach and CA-MAC by evaluating their improvement of packet loss rate over fixed TDMA scheduling approach. The

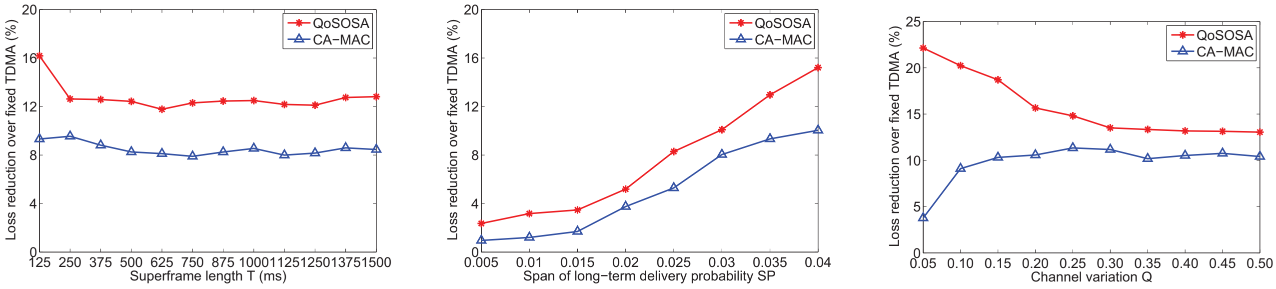

Fig. 1. Reliability performance versus a) superframe length; b) span of long-term delivery probability; c) channel variation.

performance metric is then defined as the reduction of packet loss rate over fixed TDMA approach, denoted by PLR_{reduc}, and is given by

$$PLR_{reduc} = \frac{PLR_{fix} - PLR}{PLR_{fix}} \tag{9}$$

where PLR_{fix} is the packet loss rate of fixed TDMA approach and PLR is the packet loss rate of corresponding approach for evaluation, i.e., the proposed approach or CA-MAC.

We first evaluate the reliability performance of the two approaches under different superframe length T, from 125ms to 1500ms. As shown in Fig. 1a, both approaches obtain a reduction of packet loss rate over fixed TDMA approach and the proposed approach results in a larger reduction than CA-MAC. This is because the proposed approach explores the nature of channel fading in WBAN and schedules the slots based on channel estimation rather than blindly interleaving the transmissions of nodes as is done in CA-MAC. It can be seen from Fig. 1a that PLR_{reduc} of the proposed approach first drops down to lower point and then becomes relatively stable as T increases. In the proposed approach, we schedule the slots based on most recent channel condition in the previous superframe. However, with a larger T, nodes will transmit packets in the upcoming superframe with a delivery probability closer to $\frac{P_{BG}}{Q}$ no matter what the most recent channel history is. This implies that the obtained channel information becomes less useful. Therefore, the benefit of scheduling is mitigated as T increases. When T exceeds a relatively large value, the actual delivery probability tends to approach the long-term delivery probability $\frac{P_{BG}}{Q}$, and the impact on scheduling benefit by varying T becomes trivial. We also observe that the variation of superframe length T has little impact on the PLR_{reduc} of CA-MAC. Although the average length of contention period may increase as T increases, the total packet loss rate nearly remains constant because the impact of interleaving is not highly related to the length of contention period.

We now evaluate the reliability performance of the two approaches under different channel conditions, which is quite necessary in complex time-varying WBAN channel. We vary the long-term delivery probability $\frac{P_{BG}}{Q}$ of all nodes from 0.9 to 0.99, and found that the packet loss rate reduction of the proposed approach and CA-MAC becomes stable at 4% and 1%, respectively. This indicates that $\frac{P_{BG}}{Q}$ has a negligible effect on PLR_{reduc} for both approaches. Although the packet loss rate for both approaches may reduce as $\frac{P_{BG}}{Q}$ increases, the packet loss rate of fixed TDMA also reduce since $\frac{P_{BG}}{Q}$ actually defines the delivery probability of fixed TDMA. It is interesting to note that the values of PLR_{reduc} are relatively small in this evaluation. It is due to the limited diversity among nodes, i.e., the long-term channel condition of all nodes are identical. Accordingly, we compare the reliability performance by fixing the average $\frac{P_{BG}}{Q}$ of nodes at 0.95 while varying the span of $\frac{P_{BG}}{Q}$ (denoted by SP). In other words, we randomly choose the value of $\frac{P_{BG}}{Q}$ for each node from the range between 0.95-SP and 0.95+SP. As shown in Fig. 1b, PLR_{reduc} increases as SP increases for both approaches. When SP increases, the channel diversity among nodes increases, which results in the performance degradation of those nodes with relatively low $\frac{P_{BG}}{Q}$ in fixed TDMA scheme. However, such nodes can still achieve a satisfactory delivery probability by using the proposed scheduling approach, which means the performance benefits would increase. From these results, we can conclude that the proposed approach can be efficiently used in heterogeneous WBAN.

We also evaluate the reliability performance under a serial of practical values of Q (from 0.05 to 0.5), which signifies the speed of channel variation. As shown in Fig. 1c, when Q increases, PLR_{reduc} in the proposed approach decreases whereas PLR_{reduc} in CA-MAC increases. In the proposed approach, when Q is larger, the delivery probability of each node approaches to $\frac{P_{BG}}{Q}$ faster in the upcoming superframe. Therefore, the benefits brought by adjusting transmission order become less, which is similar to the case of larger T in Fig. 1a. With a smaller Q, the channel condition in the upcoming superframe is more relevant to that of most recent transmission and adjusting transmission order accordingly could bring more benefits. However, with a small Q in CA-MAC, the channel variation is relatively small and hence the benefits from timely spreading the transmission chances become slight.

B. Energy Efficiency

Energy consumption is highly influenced by the activity of nodes. It may not be fair to evaluate energy efficiency simply by comparing the absolute value of energy consumption of

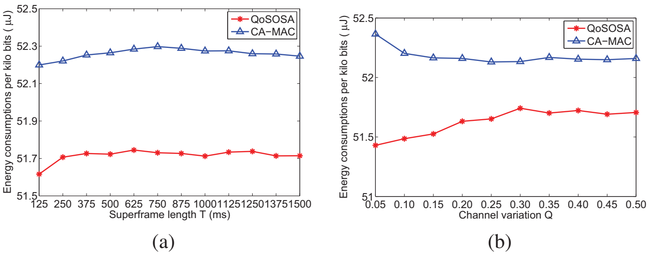

Fig. 2. Energy efficiency performance versus a) superframe length; b) channel variation.

two networks without specifying the activities of nodes. For example, two networks with the same energy consumption may differ greatly in their overall throughput. Therefore, the energy consumption per kilo bits is used here to evaluate the performance of energy efficiency. We also evaluate the impact of different parameters on the performance of energy efficiency. The range of parameter variations is the same as that of reliability evaluations.

In Fig. 2a, we show the energy efficiency performance of the proposed approach and CA-MAC as a function of superframe length T. It can be seen from the figure that the proposed approach presents a superior performance in energy efficiency. The proposed approach schedules slots to nodes with relatively good channel condition and therefore reduces the energy wastage from transmission failure. However, the bandwidth has not been efficiently used and data collisions are introduced in CA-MAC due to the exponential backoff during contention period. As shown in Fig. 2a, the energy consumption firstly increases and then becomes relatively stable as T increases in the proposed approach. This is because the channel estimation becomes less important when T becomes large. As a result, nodes may not be able to obtain good slots and to transmit packets as efficiently as they may with a small T. Thus more energy wastages from transmission failure are introduced.

We also evaluate the impact of various settings of channel conditions on the energy efficiency performance, e.g., $\frac{P_{BG}}{Q}$, SP, and Q. From the simulation results, we arrive at the conclusion that the proposed approach still outperforms CA-MAC in energy efficiency for all kinds of channel conditions. Besides, we also observe that the energy efficiency of both approaches is highly related to their packet loss rate in all channel conditions. Specifically, we show the energy efficiency of both approaches by varying Q in Fig. 2b. When Q increases, the energy consumption per kilo bits of the proposed approach and CA-MAC increases and decreases, respectively. This behavior is similar to the behavior of packet loss rate when Q increases for both approaches. This is due to the fact that energy consumption of both approaches result mainly from transmission and reception. In other words, if an approach is not able to efficiently schedule transmissions with lower packet loss rate, it may cause more extra energy consumption. Similarly, such rational also applies to the evaluations when $\frac{P_{BG}}{Q}$ or SP is varied. Due to the lack of space, we can not include these two figures.

V. Conclusion

In this paper, we present a QoS-driven scheduling approach using optimal slot allocation to overcome technical challenges resulting from energy consumption, time-varying traffic and channel variation in WBAN. With dynamic adaptation of slot allocation based on both channel status and traffic request, sensor nodes can transmit packets with energy efficiency while satisfying QoS constraints. The proposed approach outperforms existing WBAN scheduling approaches that lack appropriate modeling and optimization under a diverse set of practical WBAN conditions. Furthermore, the proposed approach is shown to be more suitable to the heterogeneous environment of WBAN.

Acknowledgment

This work is supported in part by "the Fundamental Research Funds for the Central Universities (WK2100230002, WK2101020002)" of China, the USTC Funds for Youth Scholars (KA2101020001), and the USTC Grant Master Professor Funds (ZC9850290097).

References

[1] B. Zhen, M. Patel, S. Lee, and E. Won, "Body area network (BAN) technical requirements," IEEE P802.15-08-0037-04-0006, Jul. 2008.
[2] P. Hall *et al.*, "Antennas and propagation for on-body communication systems," *IEEE Antennas Propag. Mag.*, vol. 49, pp. 41–58, Jun. 2007.
[3] K. Y. Yazdandoost and K. Sayrafian-Pour, "Channel model for body area network (BAN)," IEEE P802.15-08-0780-11-0006, Sep. 2010.
[4] O. Omeni, A. Wong, A. Burdett, and C. Toumazou, "Energy efficient medium access protocol for wireless medical body area sensor networks," *IEEE Trans. Biomed. Circuits Syst.*, vol. 2, pp. 251–259, Dec. 2008.
[5] S. Marinkovic, E. Popovici, C. Spagnol, S. Faul, and W. Marnane, "Energy-efficient low duty cycle mac protocol for wireless body area networks," *IEEE Trans. Inf. Technol. Biomed.*, vol. 13, pp. 915–925, Nov. 2009.
[6] A. Ghildiyal, G. Balwant, and A. Amara, "Design of an ultra low power mac for a heterogeneous in-body sensor network," in *Proc. 6th International ICST Conference on Body Area Networks (BodyNets 2011)*, Nov. 2011.
[7] H. Li and J. Tan, "Heartbeat-driven medium-access control for body sensor networks," *IEEE Trans. Inf. Technol. Biomed.*, vol. 14, no. 1, pp. 44–51, Jan. 2010.
[8] Y. Tselishchev, L. Libman, and A. Boulis, "Reducing transmission losses in body area networks using variable tdma scheduling," in *Proc. 2011 IEEE International Symposium on a World of Wireless, Mobile and Multimedia Networks (WoWMoM)*, Jun. 2011, pp. 1–10.
[9] B. Liu, Z. Yan, and C. W. Chen, "CA-MAC: A hybrid context-aware MAC protocol for wireless body area networks," in *Proc. 13th IEEE International Conference on e-Health Networking Applications and Services (Healthcom)*, Columbia, MO, Jun. 2011, pp. 213–216.
[10] SMA-WiBAN, "MAC and security baseline proposal," IEEE P802.15-09-0196-02-0006, Mar. 2010.
[11] E. Gilbert, "Capacity of a burst noise channel," *Bell Systems Technical Journal*, vol. 39, pp. 1253–1256, 1960.
[12] G. L. Nemmhauser and L. A. Wolsey, *Integer and Combinatorial Optimization*, 1st ed. Wiley-Interscience, 1988.
[13] D. Davenport *et al.*, "MedWiN physical layer proposal documentation," IEEE P802.15-09-0329-00-0006, May 2009.
[14] D. Smith *et al.*, "Dynamic narrowband body area communications: Link-margin based performance analysis and second-order temporal statistics," in *Proc. 2010 IEEE WCNC*, Apr. 2010, pp. 1–6.
[15] Crossbow technology,crossbow datasheet on micaz. [Online]. Available: http://www.xbow.com
[16] J. Lofberg, "YALMIP : a toolbox for modeling and optimization in MATLAB," in *Proc. 2004 IEEE CACSD Conference*, Sep. 2004, pp. 284–289.