Energy Efficient Transmission Approach for WBAN Based on Threshold Distance

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***Abstract*—Energy efficiency is a key concern for wireless sensor nodes, especially for wireless body area network (WBAN) in which sensors operate in close vicinity to, on or even inside a human body. In this paper, we first present a system-level energy consumption model associated with transmission distance d and transmission data rate over on-body wireless communication link. Then, based on the analysis of tradeoff between circuit energy and transmission energy on distance, a threshold distance d_{th} which is responsible for the proportion of transmission energy and circuit energy is derived for energy saving in WBAN. With the case of $d \leq d_{\text{th}}$, since circuit energy is comparable with transmission energy consumption, the total energy consumption can be saved by optimizing the transmission data rate R. Simulation results show that a 59.77% or even more energy saving is achievable using the optimized scheme, compared with baseline scheme. With $d > d_{\text{th}}$, since the total energy consumption is monotonically decreasing with respect to time t, an offline algorithm is applied to energy saving by prolonging transmission time within the deadline time. In addition, on the basis of the offline algorithm, a battery-aware transmission approach is presented for WBAN using battery electrochemical property. Experimental results show that, using the presented battery-aware approach, 71.05% and 60.81% energy saving can be obtained, in comparison with the baseline and offline schemes, respectively.**

***Index Terms*—Energy efficiency, wireless body area network (WBAN), threshold distance, battery, recovery effect.**

I. INTRODUCTION

With recent advances in wireless networks, low-power microelectronics, and mobile computing technologies, Wireless Body Area Networks (WBANs) has become a focus of intensive research activities in recent years, which provide a solution for the aging population in many developed country and the rising costs of medical care to improve medical health and quality of life [1]–[4]. For example, by the worn and/or implanted sensors, the sensing physiological parameters, e.g., heartbeat, body temperature, and ECG, are sent to the remote medical server for further real-time analysis and diagnosis [5].

However, sensor nodes in WBANs are powered by the limited-energy batteries, which results in the fact that energy efficiency becomes a key issue [6]. Generally, in a sensor node, the total energy comprises circuit energy and transmission energy, which are consumed by circuit components and transmitted signal, respectively [7], [8]. Although circuit energy consumption is increasingly smaller with development of low-power microelectronics, it cannot be ignored for WBANs in which the transmission distance is at most 3m or 5m (for some special cases) [9].

Therefore, a variety of energy efficient approaches have been presented and investigated for energy saving over the past few years [7], [10]–[14]. For example, In [7], Cui *et al.* presented an energy-constrained modulation optimization to save energy. [10] presented an energy-efficient algorithm for minimizing the transmission energy to transmit packets over wireless link by increasing transmission duration. Li *et al.* in [11] built up a system level energy model for all the components in the RF and analog front-end to aim at scaling down the energy consumption by analyzing and adjusting some parameters. Zhu *et al* provided a procedure for the creation of an energy efficient sensor network organization to extend the lifetime of multi-hop sensor networks [12], and [13] presented three widely used digital modulation schemes (i.e. MQAM, MPSK, and noncoherent MFSK) for the energy consumption on the wireless sensor network links. In [14], Abouei *et al.* presented a physical protocol using the rateless code with FSK modulation scheme for WBAN Medical Implant Communication Service (MICS), which can achieve about 80% energy saving, compared to IEEE 802.15.4 standard with the same structure. However, there is little literature to investigate the energy optimization based on the transmission distance and transmission data rate for WBANs.

In this paper, under the consideration of MPSK modulation defined by IEEE 802.15.6 standard for the standardization of WBAN [15], we build up a system level energy consumption model, which comprises circuit energy and transmission energy with respect to distance d and transmission data rate R. Based on the analysis of the total energy consumption, we find

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Manuscript received February 15, 2015; revised May 3, 2015 and May 12, 2015; accepted May 13, 2015. Date of publication May 21, 2015; date of current version July 21, 2015. This work was supported in part by the Shenzhen Basic Research Funds under Grant CXZZ20140417113430629, Grant JCYJ20120615140419045, Grant JCYJ20130401170306884, and Grant JCYJ20140417113430655, in part by the National Natural Science Foundation of China under Grant 61379136, and in part by the Enhancing Program of Key Laboratories of Shenzhen City under Grant ZDSY20120617113021359. This paper was presented in part at the IEEE International Conference on Wireless Communications and Signal Processing (WCSP), Hangzhou, China, November 2013. The associate editor coordinating the review of this paper and approving it for publication was Prof. Aime Lay-Ekuakille. *(Corresponding author: Ye Li.)*

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Digital Object Identifier 10.1109/JSEN.2015.2435814

a fact that, when the transmission distance d is less than a threshold distance d_{th}, the circuit energy is comparable to transmission energy. In this work, the threshold distance d_{th} is derived for the optimization of the total energy consumption, which is a convex function and can be saved by optimizing the transmission data rate R when $d \leq d_{th}$. As for the case $d > d_{th}$, many packet schedule algorithms are employed to minimize the energy consumption with satisfaction of constraints (e.g., deadline time) [7], [10], [16] under the assumption of the linear battery model. However, according to the diffusion principle [17], Li-ion battery has *recover effect* because of its nonlinearity. If given a period of idle time, battery charge can be recovered [18]. Therefore, based on the battery electrochemical characteristics, a battery-aware energy-efficient approach is presented for WBAN. Simulation results shows that, the presented battery-aware approach has superior energy-efficient performance, in comparison with the pure offline algorithm. Note that, Compared to the case $d > d_{th}$, the battery recovery effect is not considered for the case $d \leq d_{th}$, because the duty cycle is very high, and thus there is almost no idle time to recovery charge for battery [18].

The rest of the paper is organized as follows. In Section II, a system level energy model is established over the on-body wireless communication link. Based on the energy analysis, Section III derives the threshold distance, and numerical results are evaluated to show the effect of the optimized scheme and baseline scheme for the case of $d \leq d_{th}$ in Section IV. By applying the battery recovery characteristics, in Section V, a battery-ware approach is presented for the energy saving on the basis of the offline algorithm when $d > d_{th}$, together the simulation results given in Section VI. Final conclusions are presented in Section VII.

II. SYSTEM LEVEL ENERGY CONSUMPTION MODEL

Because of the influence of body on the radio electromagnetic wave propagation, it is very important to build up the channel characterization from medical and/or non-medical devices, which are placed on, close to, or inside the human body [19]. To derive the path loss model for WBAN, in [9], the sensor nodes are defined as implant, body surface, and external nodes. Based on these node definitions, the IEEE 802.15.6 devices can be operated at the identified scenarios, which can be grouped into different classes by the same Channel Models (CM) in TABLE 2 [9], together with their description and frequency band. For example, CM3 is a radio communication link from body surface to body surface covering the frequency band 13.5, 50, 400, 600, 900MHz, 2.4, 3.1–10.6GHz, whereas CM1 is a link for implanted nodes operating in frequency band $402 - 405MHz$, by which, the data sensed by implanted biosensor is transmitted to a external Central Processing Unit (eCPU) across tissues in the human body. The possible communication links for WBAN are illustrated in Fig. 1. In this paper, CM3 is applied from body surface to body surface between a wearable biosensor and the eCPU.

For convenience, the link used to transmit signal from the biosensor to eCPU is defined as uplink to send data; conversely, it is called as downlink to only receive control information. As for the biosensor in WBAN, the data to be transmitted in uplink is much more than that of downlink. The half-duplex operation is thus adopted in this work because of many other advantages presented in [14]. More importantly, unlike the eCPU having a energy source, the biosensor powered by a battery is energy-constrained. Our main purpose is to reduce the biosensor energy consumption for achieving a significant energy saving and extending the battery life time.

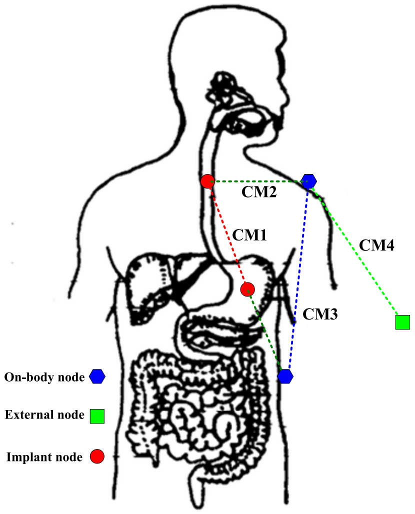

Fig. 1. Possible communication links for WBAN [20].

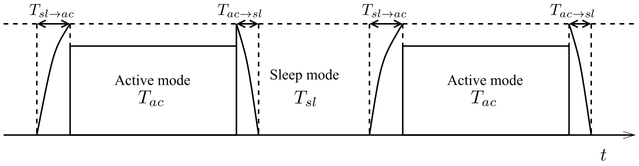

Fig. 2. A biosensor operation in an on-body WBAN [14].

Generally speaking, in a WBAN communication system, the biosensor operates in a duty-cycling mode depicted in Fig. 2 [14]. Once receiving the control information from the eCPU before the uplink transmission period, the biosensor is wake up to Active-mode (denoted by T_{ac}) from Sleep-mode (denoted by T_{sl}) after a short-time TRANSIENT-mode (denoted by $T_{sl\rightarrow ac}$). During the ACTIVE-mode, the weak raw signal sensed by the wearable biosensor is passed through amplification and filtering processes, then the filtered signal is modulated by a modulation scheme and is transmitted to eCPU across the communication link around the human body. When finishing transmitting the sensed data, the biosensor would switch to SLEEP-mode with duration T_{sl} after a short-time TRANSIENT-mode (denoted by $T_{ac\rightarrow sl}$) for energy saving, and at this time, most of the circuits of the transceiver are powered off. Such process comes round full circle. Therefore, the duty-cycling covers ACTIVE-, SLEEP-, and TRANSIENT-modes to make biosensor keep on or off. At the TRANSIENT-mode, the transient duration denoted as T_{tr} consists of the switching time from sleep mode to active mode ($T_{sl\rightarrow ac}$) and the reverse process ($T_{ac\rightarrow sl}$). It is worth noting that, the transition duration $T_{tr} = T_{sl\rightarrow ac} + T_{ac\rightarrow sl}$ is an order of magnitude smaller than the ACTIVE-mode duration T_{ac}, which results that the transient energy can be assumed negligible [7], [14]. On the other hand, for future generation CMOS circuits which would be built with the smaller geometries, but the power consumed in SLEEP-mode cannot be approximated to zero as before and should be taken into account [11].

Based on the above analysis and assumptions, the energy consumption per information bit for transmitting L bits in a deadline time T can be formulated as

$$E_{bit} = \frac{P_{ac}T_{ac} + P_{sl}T_{sl}}{L} \tag{1}$$

where P_{ac}, P_{sl} are the power consumed in the ACTIVE-duration T_{ac} and SLEEP-duration T_{sl}, respectively. Note that, $T_{ac} + T_{sl} = T$.

In addition, the ACTIVE-mode power P_{ac} is mainly composed of the power amplifier (PA) power P_{PA} and circuit power P_C in the whole signal path, where P_C could be assumed as a constant. The PA power P_{PA} consists of the transmission power P_t and the amplifier circuit power $P_{amp} = \beta P_t$, where $\beta = \frac{PAR}{\rho} - 1$ with the PA drain efficiency ρ and the peak-to-average ratio (PAR) [7]. Thus, we have

$$P_{ac} = P_{PA} + P_C \tag{2}$$

with $P_{PA} = P_t + P_{amp} = 1 + \beta P_t = \frac{PAR}{\rho} P_t$.

Unlike the traditional wireless communication systems, the path loss for on-body WBAN is both distance and frequency dependent [9]. Some path loss models for WBAN have been measured and summarized in [9] by different path loss functions and parameters over various frequency band. In this paper, the link CM3 is applied with frequency band over $950 - 956MHz$, and thus the corresponding path loss model is given by

$$PL[dB] = a\_loss \lg d + b\_loss + N\_loss \tag{3}$$

where a_loss and b_loss are coefficients of linear fitting, d is the Tx-Rx distance in *mm*, and N_loss is a normally distributed variable with standard deviation δ_N.

Therefore, from Eq. (3), the average transmission power P_t represented by the received signal power P_r can be written as

$$P_t = P_r 10^{\frac{b\_loss + N\_loss}{10}} d^{\frac{a\_loss}{10}} \tag{4}$$

Assume MPSK modulation is employed by IEEE 802.15.6 standard [15]. Then, the Bit Error Rate (BER) P_b at the receiver for MPSK ($M \geq 4$) can be expressed as [7], [11]

$$P_b = \frac{2}{b} Q(\sqrt{\frac{4P_r}{N}} \sin \frac{\pi}{2^b}) \leq \frac{1}{b} e^{-\frac{2P_r}{N} \sin^2 \frac{\pi}{2^b}}$$

where modulation level $b = \log M \geq 2$, $N = BN_0N_f$ with bandwidth B, $\frac{N_0}{2}$ is the power spectral density of noise, $N_f = \frac{N_{total}}{BN_0}$ is the receiver noise figure, and N_{total} is the power of the noise introduced by the receiver front-end. By substituting P_b into (4), the received signal power is

$$P_r = -\frac{BN_0N_f}{2} \frac{\ln(bP_b)}{\sin^2 \frac{\pi}{2^b}} \tag{5}$$

with the bandwidth for PSK $B = \frac{1+\alpha}{b} R$, where α denotes the roll-off factor of the pulse-shaping filter, $R = L/T_{ac}$ denotes the transmission data rate. Then, from Eqs. (1) to (5), we have

$$E_{bit} = \frac{\frac{PAR}{\rho} 10^{\frac{b\_loss + N\_loss}{10}} d^{\frac{a\_loss}{10}} \left(-\frac{BN_0N_f}{2} \frac{\ln(\frac{1+\alpha}{B} P_b R)}{\sin^2 \frac{\pi}{2^{\frac{1+\alpha}{B} R}}}\right)}{R} + \frac{P_C - P_{sl}}{R} + \frac{P_{sl}T}{L} \tag{6}$$

Both d and R are variables to be optimized in the next section, while the others are constants.

TABLE I

PARAMETERS OF THE PATH LOSS MODEL COVERING FREQUENCIES OF $950 - 956MHz$ FOR ON-BODY COMMUNICATION [9]

Parameters	Hospital Room	Anechoic Chamber
a_loss	15.5	28.8
b_loss	5.38	23.5
δ_N	5.35	11.7

III. THRESHOLD DISTANCE

From Eq. (2), we know the fact that the total energy E_T comprises circuit energy E_C and transmission energy E_{Tr}. Unlike the tradition wireless communication systems without consideration of E_C, in the short-distance WBAN, circuit energy E_C is comparable to transmission energy E_{Tr}, and thus can no longer be ignored [7], [14]. Therefore, from Eq. (6), we can image that E_C is the main contribution of E_T when the transmission distance d is less than a threshold distance d_{th}. As for this case, we can optimize the transmission data rate R to reduce the total energy consumption in Section IV, since $E_C = P_C \cdot T_{ac}$. When $d > d_{th}$, much literature has presented many energy efficient approaches [10]–[14], e.g., by prolonging the transmission time [10], and we also have discussed this case based on the battery characteristics in Sections V and VI. In the following subsections, we would like to find the threshold distance d_{th} for the energy efficiency on the tradeoff between E_C and E_{Tr}.

A. Energy Consumption Analysis

Before obtaining the threshold distance, we firstly present the energy consumption analysis to discuss the relationships among E_T, E_C, E_{Tr}, d and data rate R. According to [9], TABLE I summarizes the corresponding parameters in (3) associated with CM3 covering frequency band $950-956MHz$ in a hospital room and an anechoic chamber. Other parameters in Eq. (6), together with the path loss model parameters, are listed in TABLE II [7], [9], [14], [15], which, certainly, can be changed in accordance with other scenarios.

Figure 3 exhibits the effect of E_{bit} with respect to R for different values of distance d. It is seen that the energy consumption is convex with R as proved in [7] and not a monotonically increasing function of R. This is because transmission energy consumption E_{Tr} increases exponentially with the increasement of d by Eq. (4), while circuit energy consumption E_C is

TABLE II
PARAMETERS IN A HOSPITAL ROOM FOR ON-BODY COMMUNICATION LINK CM3 [7], [9], [14], [15], [22]

$f_c = 951.10MHz$	$T = 100ms$
$a\_loss = 15.5$	$L = 2Kb$
$b\_loss = 5.38$	$P_c = 12.5mW$
$\delta_N = 5.35$	$P_{sl} = 0.5mW$
$B = 400kHz$	$P_b = 10^{-5}$
$\frac{N_0}{2} = 10^{-16}W/Hz$	$\rho = 0.5$
$N_f = 10dB$	$PAR = 1$
	$\alpha = 0.25$

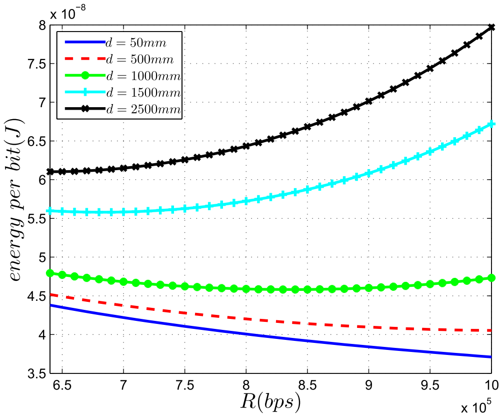

Fig. 3. Energy consumption with R and d.

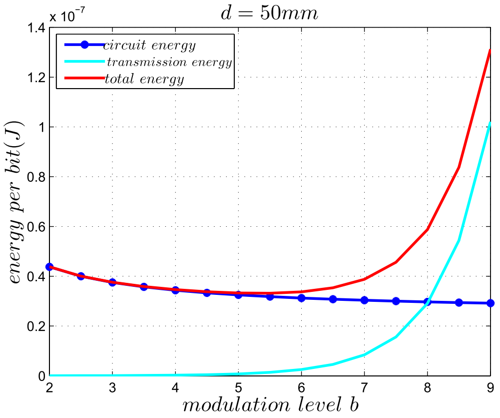

Fig. 4. Energy consumption versus modulation level for CM3 channel.

independent of d. Therefore, a threshold distance d_{th} can be found by the trade-off between E_C and E_{Tr}. That is, when $d > d_{th}$, E_{Tr} is the main contribution of E_T being a monotonically increasing function of R (see the black curve for the case *d=2500 mm* in Fig. 3). In this case, the energy consumption can be reduced by using some packet schedule algorithms [10]; when $d \leq d_{th}$, E_C is comparable to E_{Tr} (see the green curve at *d=1000 mm* in Fig. 3), and cannot be negligible. In this case, The total energy E_T has a minimum point at an optimal R, and thus can be saved by optimizing R.

Figure 4 further shows the relationships between E_T, E_C, and E_{Tr} by the definition of the bandwidth B, when *d=50 mm* as an illustrative example. Evidently, the transmission energy consumption E_{Tr} increases with b (or R, since $b \propto R$), while circuit energy consumption E_C decrease with b (or R), and the total energy E_T is convex. Therefore, there is a tradeoff between E_C and E_{Tr} to minimize E_T. For example, E_T is minimal when $b \approx 6$ in Fig. 4.

B. Computation on Threshold Distance

As above mentioned and in [10], the total energy is strictly convex with R. Therefore, based on the tradeoff between the transmission energy and the circuit energy, we can find the threshold distance d_{th} by the derivative of E_{bit} with respect to R at the minimum transmission data rate R_{min}. Assume that L bits information should be transmitted within the deadline time T. Then, $R \geq \frac{L}{T}$. Additionally, from $b = \frac{1+\alpha}{B}R \geq 2$, we have

$$R = \frac{B}{1+\alpha}b \geq \frac{2B}{1+\alpha}$$

Thus, the minimum transmission data rate

$$R_{min} = max\{\frac{L}{T}, \frac{2B}{1+\alpha}\} \tag{7}$$

Combining Eqs. (6) and (7), we have

$$d_{th} = \{d : \frac{\partial E_{bit}}{\partial R}|_{R=R_{min}} = 0\} \tag{8}$$

To minimize the total energy, we should determine the range of transmission data rate to make $R \in [R_{min}, R_{max}]$ with the maximum rate R_{max}. Since the WBAN devices operate in the vicinity to a human body, they should transmit lower power when possible in order to reduce interference to other devices and systems, and to protect the safety of the human body. The maximum transmit power denoted as P_{max} is limited by local regulatory bodies [15]. That is, the transmit power must satisfy $P_t \leq P_{max}$. By Eqs. (4) and (5), we have

$$\begin{aligned} R_{max} = \{R : 10^{\frac{b_{loss}+N_{loss}}{10}} d^{\frac{a_{loss}}{10}} (-\frac{BN_0N_f}{2} \frac{\ln(\frac{1+\alpha}{B}P_bR)}{\sin^2\frac{\pi}{2^{\frac{1+\alpha}{B}R}}}) \\ = P_{max}\} \end{aligned} \tag{9}$$

Assume the maximum transmit power $P_{max} = 1.5W$ (i.e., Effective Radiated Power, ERP) by the Federal Communication Commission (FCC) [9], together with the parameters in TABLE II. Then, from Eq. (8), we can compute

$$d_{th} = \left\{d : \frac{\partial E_{bit}}{\partial R}|_{R=R_{min}} = 0\right\} = 2499.8\ (mm) \tag{10}$$

IV. NUMERICAL EVALUATION FOR $d \leq d_{th}$

In this section, we would like to provide the simulation results and analysis for the case $d \leq d_{th}$, and, in the subsequent sections, a battery-aware transmission approach is presented for the case $d > d_{th}$, together with its simulation results analysis.

For the consideration $d \leq d_{th}$, the total energy can be saved by optimizing R through an appropriate convex optimization algorithm, which is denoted by *optimized scheme*. For comparison, the scheme which just simply sets the transmission

TABLE III

PARAMETERS AND RESULTS FOR *Optimized/Baseline* SCHEMES

$d(mm)$	10	100	500	1000	2000
$R_{max}(Mbps)$	4.0003	3.1705	2.5897	2.3392	2.0884
$R_{opt}/R_{min}(Kbps)$ $(Optimized/Baseline\ Scheme)$	2217.1/480	1490.7/480	1019.7/480	837.54/480	681.59/480
$E_{bit}(10^{-8}J)$ $(Optimized/Baseline\ Scheme)$	0.8549/2.1253	1.2062/2.1368	1.8010/2.2675	2.3307/2.5424	3.3294/3.3471
$Percent\ \ of\ \ Saving$	59.77%	43.55%	20.58%	8.32%	0.53%

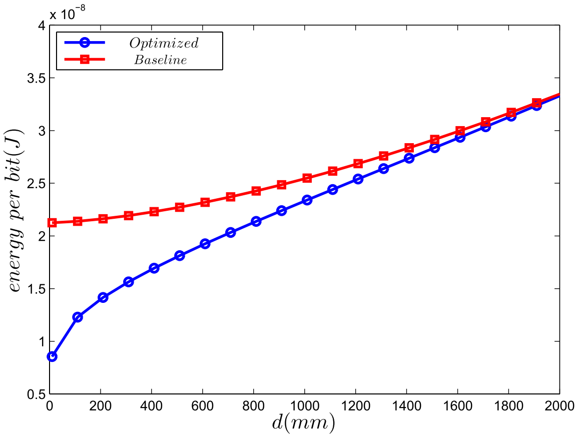

Fig. 5. Performance of the energy consumption by the two schemes.

data rate as the minimum R_{min} is denoted as the *baseline scheme*. Simulation results show the feasibility of d_{th} by using realistic parameters over CM3. Furthermore, when $d \leq d_{th}$, the total energy could be saved by using the *optimized scheme* compared to the *baseline scheme*. Note that, all the simulation are based on the IEEE 802.15.6 standard.

Therefore, as analyzed in Subsection III-A, when $d \leq d_{th} = 2499.8mm$ computed by Eq. (10), the total energy can be minimized by using some convex optimization algorithms, e.g., interior point method [24]. Based on the analysis in Subsection III-B, the problem to optimize the total energy consumption could be summarized as in mathematics.

$$\begin{cases} \text{Minimize} & E_{bit} \\ \text{Subject to} & R_{min} \leq R \leq R_{max} \end{cases} \tag{11}$$

where E_{bit} is convex over $d \leq d_{th}$ and all the constraints are simple linear constraints, which can be efficiently solved by interior point method converting the constrained problem into an unconstrained one [7]. Thus, we can obtain the corresponding optimum parameters and energy consumption. For *baseline scheme*, it is rational that the transmission data rate is assumed to be set as the minimum rate, i.e., $R = R_{min} = 480\ Kbps$ by Eq. (7).

The simulation results for the *optimized* and *baseline* schemes are listed in TABLE III and Fig. 5, where R_{opt} represents the optimal rate from (11) for the *optimized* scheme and the minimal rate R_{min} for the *baseline* scheme, E_{bit} is the minimum energy consumption per information bit, and *Percent of Saving* is responsible for the percent of the total energy saved by the *optimized* scheme, compared to the *baseline* scheme.

From TABLE III, we know the fact that R_{max} from Eq. (9) decreases along with the increase of d, and so is the optimum rate R_{opt}. This is because the transmission energy consumption is monotonically increasing with d from Eqs. (4) and (5), while the circuit energy consumption is independent of d, and thus the transmission data rate R is smaller and smaller. Moreover, the closer d is to d_{th}, the closer the optimum rate R_{opt} is to the minimum rate R_{min} because of the bigger proportion of the transmission energy to the circuit energy consumption. In other words, the energy efficiency by optimizing R is becoming less and less with decrease of the gap between d and d_{th}. For example, when $d = 10\ mm$, a 59.77% energy saving is achievable by using *optimized* scheme, compared to the *baseline* scheme, whereas only 0.53% energy is saved when $d = 2000\ mm$. Therefore, the smaller d is, the more percent of energy can be saved by employing the *optimized* scheme. These simulation results are consistent with the performance shown in Fig. 3, and they implicitly indicate that the transmission energy consumption is susceptible to d. In a word, when $d \leq d_{th}$, the transmission energy is dominant in the total energy consumption, which can be saved by optimized the transmission data rate R, and the energy performance for the case $d > d_{th}$ would be considered in the following sections.

V. BATTERY-AWARE ENERGY EFFICIENT TRANSMISSION APPROACH FOR $d > d_{th}$

In Section III, we know that, since the transmission distance is short, the circuit energy consumption E_C can be comparable to transmission energy consumption E_{Tr}, and cannot be ignored. Thus, there is a tradeoff between transmission energy consumption E_{Tr} and circuit energy consumption E_C on threshold distance d_{th}; when transmission distance $d \leq d_{th}$, energy can be saved by increasing the transmission data rate R. The related simulation results can be shown in TABLE III and Fig. 5 in Section IV. In this section, we would like to present a battery-aware energy efficient approach for WBAN when $d > d_{th}$, and its simulation results is given out in Section VI.

A. Local Offline Scheduling Algorithm

From [10] and [21], the total energy consumption is strict convex and decreasing with respect to time t. Thus, energy

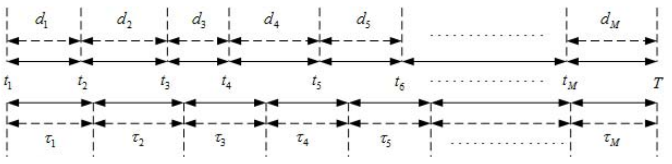

Fig. 6. Data packets transmission within deadline time T.

consumption can be saved by prolonging transmission time. But, some vital physiological parameters should be transmitted within a deadline time in WBAN. Assume that M data packets with equal length L should be transmitted within deadline time T, i.e., $[0, T]$, as shown in Fig. 6, where, t_i is denoted by the arrival time for the ith data packet, d_i is the time interval with $i = (1, 2, 3, \cdots, M-1)$, and thus $d_i = t_{i+1} - t_i$. The first data packet is assumed to be arrived at $t_1 = 0$, and since M data packets should be transmitted with the deadline time T, we thus have $\sum_{i=1}^{M} d_i = T$ and the interval is $d_M = T - t_M$ for the last data packet.

Let $\vec{\tau} = (\tau_1, \tau_2, \cdots, \tau_M)$ denote by transmission time. For analytical convenience, from (6), energy consumption for each bit can be reformulated as follows by using τ_i

$$\begin{aligned} E_{bit}^{i} &= \frac{\frac{PAR}{\rho} 10^{\frac{b\_loss+N\_loss}{10}} d^{\frac{a\_loss}{10}} \tau_i \left(-\frac{BN_0N_f}{2} \frac{\ln\left(\frac{1+\alpha}{B} P_b \frac{L}{\tau_i}\right)}{\sin^2 \frac{\pi}{2^{\frac{1+\alpha}{B}\frac{L}{\tau_i}}}}\right)}{L} \\ &\quad + \frac{P_c - P_{sl}}{L}\tau_i + \frac{P_{sl}T}{L} \\ &= w_i(\tau_i) \end{aligned} \tag{12}$$

with the transmission data rate of the ith packet $R_i = L/\tau_i$. So, (6) can be changed into

$$E_{bit} = \frac{\sum_{i=1}^{M} E_{bit}^{i}}{M} = \frac{\sum_{i=1}^{M} w_i(\tau_i)}{M} = \sum_{i=1}^{M} w(\tau_i) = w(\vec{\tau}) \tag{13}$$

where $w(\tau_i) = w_i(i)/M$.

As the above discussion, E_{bit} and E_{bit}^{i} are strict convex and decreasing with respect to transmission time, and thus can be saved by prolonging transmission time (i.e., reducing the transmission data rate). However, to guarantee M data packets be able to transmitted within deadline time T with an optimal energy consumption, transmission time should be satisfied with the following two feasibility conditions and the optimal condition presented in [10].

Feasibility Conditions:

- *For any* $k \in [1, M)$, *we have* $\sum_{i=1}^{k} \tau_i \geq \sum_{i=1}^{k} d_i$,
- $\sum_{i=1}^{M} \tau_i \leq T$,

which shows that, data packet can be transmitted, until it arrives, and, M data packets must be transmitted within the deadline time T.

Optimal Condition 1: With the satisfaction with the feasibility condition, the sum of all the transmission time should be in close proximity to the deadline time, i.e., $\sum_{i=1}^{M} \tau_i = T$.

Optimal Condition 2: Since energy consumption (13) is strict convex, $\tau_i \approx \tau_{i+1}$ *with* $1 \leq i \leq M$.

The above two optimal conditions shows that, for the energy efficiency, the total transmission time for M packets should fully cover the deadline time, and the adjacent transmission time should be equal approximately. Therefore, by the above feasibility and optimal conditions, the offline algorithm can be designed and summarized as shown in the following Algorithm.

Algorithm 1 Offline Scheduling Algorithm

```
1) Initially, $\tau_i = d_i (i = 1, 2, \cdots, M)$, and select a
   permissible error $\varepsilon$;
2) By Eq. (16), compute the maximum $E_{max} = w(\tau_{min})$
   and the minimum $E_{min} = w(\tau_{max})$;
3) compute $E_{mid} = \frac{E_{min}+E_{max}}{2}$, and
   $\tau_{mid} = \{\tau : w(\tau) = E_{mid}\}$;
4) For $k = 1 : M$,
       if $\sum_{i=1}^{k-1} \tau_i + \tau_{mid} \geq \sum_{i=1}^{k} d_i$,
           $\tau_k = \tau_{mid}$;
       else
           $\tau_k = \sum_{k=1}^{k} d_i - \sum_{i=1}^{k-1} \tau_i$;
5) If $\sum_{i=1}^{M} \tau_i < T$, $E_{max} = E_{mid}$;
   else if $\sum_{i=1}^{M} \tau_i > T$, $E_{min} = E_{mid}$;
6) Repeat steps 3)-5), till $(1 - \varepsilon)T \leq \sum_{i=1}^{M} \tau_i \leq T$. Then,
   $\vec{\tau} = \vec{\tau}^*$ is the optimal transmission time.
```

B. Battery Characteristics

Generally speaking, a biosensor nodes is powered by a Li-ion battery, which has *recovery effect* by its electrochemical property [17], [21]. Due to electrochemical reactions between electrode and active materials near the electrode, battery can deliver power. However, along with the depletion of active materials, a concentration gradient would be formed inside the battery, which would lead to the exhaustion of active materials on the surface of electrode. In fact, there exists some active materials inside the battery, which are not on the surface of the electrode. Therefore, if given a period of idle time (or sleep time) before exhaustion, the active materials would diffuse to the surface or vicinity of electrode in the battery [17], [23] to make the concentration gradient flattened. By this way, the unavailable charge can be changed into available charge after a period of idle (or sleep) time [17], [23].

From [21] and [23], the recovered energy $v(\sigma)$ is a concave function and can be simply expressed by an exponential function over the idle time σ, which is written as follows.

$$v(\sigma) = \alpha(1 - e^{-\sigma}) \tag{14}$$

where α is a parameter used to show the recovery capacity. Eq. (14) shows that the charge of battery can be recovered by prolonging idle time (or sleep time). As shown in Fig. 7 with $\alpha = 0.1$, at the beginning, the recovery effect is very obvious, and along with the increasing of sleep time, battery is hardly recovered.

C. Battery-Aware Energy Efficient Transmission Approach

Since battery charge can be recovered at idle time, there exists a tradeoff among the idle time, transmission time and deadline time for energy efficient transmission. On the

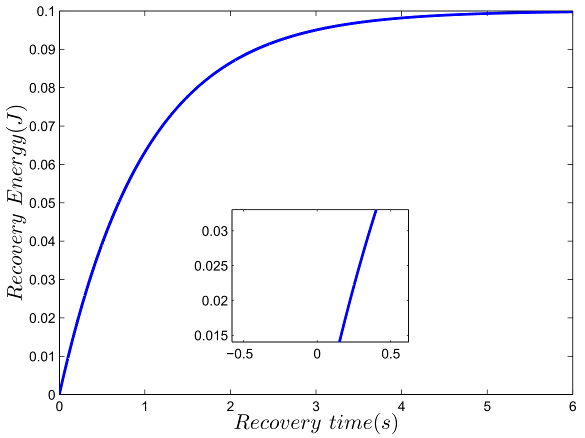

Fig. 7. Recovery effect for Li-ion battery.

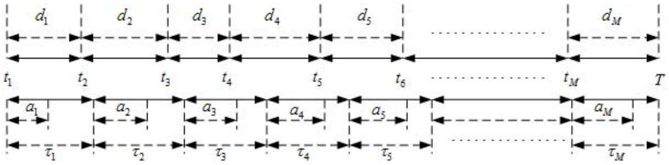

Fig. 8. Data packets transmission with battery characteristics within deadline time T.

one hand, energy must be consumed for each transmission; one the other hand, at each transmission, part of energy can be recovered by the battery's characteristics [21]. That is, if we let battery "rest" for a period of time after a transmission time, much more energy can be saved, as shown in Fig. 8, in which, τ_i, a_i, $s_i = \tau_i - a_i$ are denoted by the optimal transmission time, actual transmission time and idle time, respectively. Other parameters are defined by the same definition as that in Fig. 6. Then, by combining Eqs. (12) and (14), the optimal energy consumption $e_i(\tau_i)$ for the ith data packet over transmission time τ_i is reformulated as follows.

$$e_i(\tau_i) = inf_{0<a_i<\tau_i}\big(w_i(a_i) - v(s_i)\big) \tag{15}$$

where $w_i(\cdot)$ is already defined in (12), $v(s_i) = v(\tau_i - a_i)$ is denoted by the recovery energy derived from Eq. (14) over the idle time s_i. In other words, each energy consumption $e_i(\tau_i)$ over transmission time τ_i is equal to the sum of actual transmission energy consumption $w_i(a_i)$ and recovery energy consumption $v(s_i)$. Therefore, the total energy consumption for M data packets is

$$\begin{aligned} e(\vec{\tau}) &= \frac{\sum_{i=1}^{M} e_i(\tau_i)}{M} \\ &= \frac{1}{M}\sum_{i=1}^{M} inf_{0<a_i<\tau_i}\big(w_i(a_i) - v(s_i)\big) \end{aligned} \tag{16}$$

From [24], we have the following important property on the convex function.

Property: Assume that there is a function $f(x) = inf\, f_1(x_1) + f_2(x_2) + \cdots + f_n(x_n) | x_i \in \mathcal{R},\ x_1 + x_2 + \cdots + x_n = x$. *If* $f_1, f_2, \cdots, f_n$ *are strict convex,* $f(x)$ *is also strict convex.*

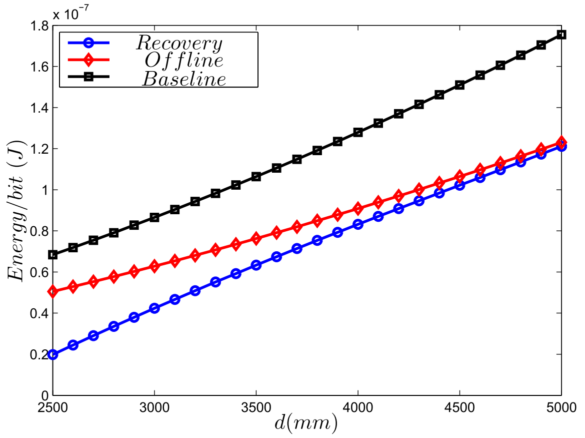

Fig. 9. Performance of energy consumption for the three transmission schemes.

Since $w_i(a_i)$ and $-v(s_i)$ are strict convex and monotonically decreasing with respect to τ_i, by the above convex property, $e_i(\tau_i)$ and $e(\vec{\tau}^*)$ are strict convex over the transmission time $\vec{\tau}^*$. As we above mentioned, there exists a tradeoff between the actual transmission time and idle time during the transmission for the smallest energy consumption. Thus, after the consideration of the recovery effect of battery, from Fig. 8, we can obtain the idle time s_i for the smallest energy consumption, which is the difference between the actual consumed energy $w_i(a_i)$ and the recovered energy $v(\tau_i - a_i)$ from battery, i.e.,

$$s_i = argmin_{0\le a_i \le \tau_i}\big(w_i(a_i) - v(\tau_i - a_i)\big). \tag{17}$$

VI. SIMULATION RESULTS FOR $d > d_{th}$

Section IV already shows the simulation performance by optimizing the transmission data rate R for the case $d \le d_{th} = 2499.8mm$ computed in Eq. (10). In this section, we would like to present the simulation results for the case $d > d_{th}$. To show the performance of the presented battery-aware energy efficient approach, the local offline algorithm and the baseline method are simulated, where, "offline" means the simulation results by using the local offline algorithm, and "baseline" means data packet would be transmitted immediately once it arrives. There is no any delay time between data packets, i.e., $\tau_i = d_i$ with $i = (1, 2, \cdots, M)$.

Assume that $M = 31$ data packets must be transmitted within the deadline time $T = 31ms$. Other parameter settings are the same as those defined in TABLE II in Section III. In addition, the communication scope is generally $0 < d < 5m$ in WBAN by the IEEE standard [15]. Thus, we would execute this experiment over the distance $d_{th} = 2499.8mm \le d < 5m$.

According to the offline algorithm and Eqs. (16) and (17), we can obtain the following computer simulation results shown in Fig. 9 and TABLE IV, where, the *Recovery* is denoted by the scheme by using battery's recovery characteristics, *Offline* is the scheme by using the local offline algorithm, and *Baseline* represents the scheme using no any method, *Percent of Saving* means the percent of energy

TABLE IV

PERFORMANCE OF ENERGY CONSUMPTION FOR *Recovery*, *Offline*, AND *Baseline* SCHEMES WITH DIFFERENT DISTANCE $d_{th} < d < 5m$

$d(mm)$	2500	3000	3500	4000	4500	5000
$E_{bit}(*10^{-8}J), Offline/Baseline$	5.05/6.84	6.28/8.65	7.63/10.64	9.09/12.79	10.65/15.10	12.31/17.54
$Percent\ \ of\ \ Saving$	26.14%	27.42%	28.32%	28.98%	29.47%	29.85%
$E_{bit}(*10^{-8}J), Recovery/Baseline$	1.98/6.84	4.23/8.65	6.33/10.64	8.32/12.79	10.22/15.10	12.11/17.54
$Percent\ \ of\ \ Saving$	71.06%	51.07%	40.49%	34.97%	32.30%	30.95%
$E_{bit}(*10^{-8}J), Recovery/Offline$	1.98/5.05	4.23/6.28	6.33/7.63	8.32/9.09	10.22/10.65	12.11/12.31
$Percent\ \ of\ \ Saving$	60.81%	32.59%	16.98%	8.44%	4.01%	1.57%

saving for the $Offline/Baseline$, the $Recovery/Baseline$, and $Recovery/Offline$ schemes, respectively. For example, when $d = 2500mm$, the energy consumption are $1.98 * 10^{-8}$, $5.05 * 10^{-8}$, and $6.84 * 10^{-8}$ for the $Recovery$, $Offline$, and $Baseline$ schemes, respectively.

Obviously, under the same simulation circumvents, in comparison with these three schemes from Fig. 9, the energy consumption is the biggest by using the $baseline$ scheme with $480Kbps$ derived from Eq. (7), which is denoted by the black square curve, while when using the $recovery$ scheme, we can achieve the smallest energy consumption, which is denoted by the blue circle curve. This is because there exists a tradeoff between actual transmission time a_i and idle time s_i. On the one hand, energy consumption can be saved by prolonging the transmission time, on the other hand, energy can be recovered over a period of idle time from battery itself. As for the $offline$ scheme, the energy consumption is reduced by prolonging the transmission time, and the battery is working on the whole duration. Therefore, its performance of energy consumption is at the middle between the $baseline$ and $recovery$ schemes. For example, when transmission distance $d = 3500mm$, compared to the $baseline$ scheme, energy can be saved about 28.32% by only using the offline algorithm. However, if the recovery effect of battery is considered on the basis of the offline algorithm, 40.4% of energy saving can be obtained for WBAN. This can further extend the battery lifetime. It is worth noting that, along with the increase of the transmission distance, the recover effect of battery is much little. For example, when $d = 5000mm$, the energy saving from recovery effect of battery is only 1.57% on the basis of the offline algorithm. This is because the transmission energy is dominated with exponential increase, which leads to the fact that the proportion of recovery energy is smaller and smaller.

In addition, as for our presented $recovery$ scheme, Figure 10 further substantiates *optimal condition 2* presented in Subsection V-A, which shows a proportion relationship between the actual transmission time a_i and the total transmission time (including the idle time) $a_i + s_i$. That is, if the transmission time ($\tau_i = a_i$) for each data packet with L is equal each other during the deadline time T (i.e., $\tau_i \approx \tau_{i+1}$), the total energy consumption is the optimal. Moreover, along with the increase the transmission distance d, the duty cycle is bigger and bigger, as shown in Fig. 11. In other words, the actual transmission time a_i is longer and longer with the increase of distance, and thus the idle time is shorter and shorter. This implies that the impact on the total energy saving is smaller and smaller for the recovery energy from battery, which is also consistent with the conclusion obtained from the simulative results shown in TABLE IV and Fig. 9.

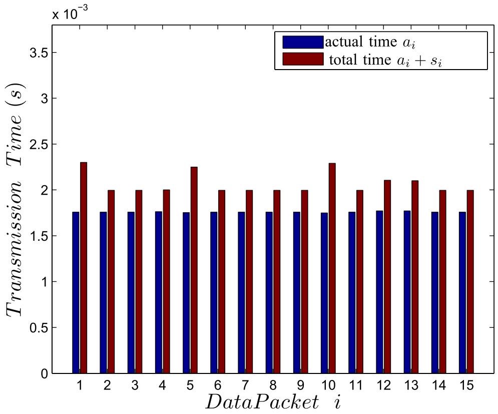

Fig. 10. Actual transmission time a_i and the total time $a_i + s_i$ when $d = 3000\ mm$.

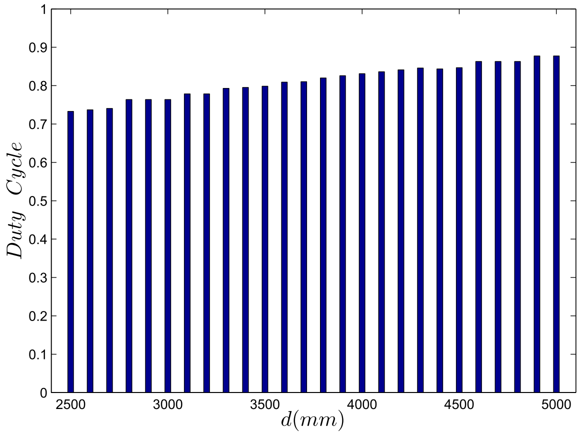

Fig. 11. Duty cycle over the different transmission distance with the optimal transmission data rate for the $recovery$ scheme.

VII. CONCLUSION

In this paper, we presented a system level energy consumption model associated with transmission distance and transmission data rate for on-body wireless communication link CM3 defined in WBAN application, together with consideration of both circuit energy and transmission energy consumption. Then, based on the tradeoff between the transmission energy and circuit energy consumption, a threshold distance d_{th} is addressed to show the proportion of circuit energy and transmission energy. Numerical valuation shows that, by using the $optimized$ scheme, a 59.77% or even more energy saving is achievable when $d \leq d_{th}$, compared to the $baseline\ scheme$. More specially, when $d > d_{th}$, by using the recovery characteristics of battery, a battery-aware transmission approach is presented for energy saving on the basis of the local offline algorithm. Simulation results substantiate that the presented battery-ware approach can improve the energy performance for wireless body area networks.

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