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Battery Friendly Packet Transmission Scheme for Body Sensor Networks

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Abstract— **For body sensor networks (BSN) nodes, extending battery lifetime is one of the key problems. In this paper, we address the problems of designing battery-friendly packet transmission policies in order to maximize the lifetime of batteries for BSN nodes under certain delay and deadline constraints. We present local optimization scheme for slack time and evaluate it with respect to battery performance. The algorithm first simplifies the analytical battery model under the premise of ensuring battery model precision, and then distributes the available slack time between two adjacent tasks. The scheme was simulated for BSN nodes, and the results demonstrate a 79% reduction in the total charge consumption of six tasks in a BSN node along with the deadline constraint of 40 mins.**

I. INTRODUCTION

The rapid development of wireless communication and low power embedded techniques, advent of miniaturized the sensors and actuators for monitoring, diagnostic, and therapeutic functions have opened up new frontiers in the race to conquer healthcare challenges.

As Body Sensor Networks (BSN) technology comes into reality, it brings the revolution of healthcare delivery. The implanted wireless sensor nodes can acquire, process, and transmit physiological data. These data can be forwarded in real time to a hospital, clinic, or central repository over a wire or wireless local area network, mobile communication network, satellite communication network.

However, most of the BSN nodes are battery-operated, and cannot be used indiscriminately because the batteries have limited energy sources. Minimizing the energy consumption of a battery-powered system is not equivalent to maximizing its battery life time. In recent years, there has been significant amount of work done in studying battery characteristics [1] [2] [3] and battery models [4] [5] [6] [7]. Among these work, [4] proposes an accurate analytical charge-based model for battery simulation, which is adopted in our paper. By the battery characteristics, battery-aware routing, task scheduling, and MAC protocols are presented. [8] [9] propose battery-aware routing algorithms to maximize the network lifetime by making full use of battery recovery effect and rate capacity effect respectively. In task scheduling, all the algorithms [10] [11] shape the load current profile in accordance with the battery non-linearity. Another scheduling scheme that adjusts the delay of different system components of a communication system such that the discharge profile is battery-friendly has been proposed in [12]. The authors in [13] propose a novel battery aware MAC scheduling scheme with the consideration of the nodes in the network and the contending of the channels.

Unlike energy minimization, battery-charge optimization requires the specification of a time at which the battery charge is to be minimized [11] There has been some effort in designing battery-aware packet transmission schemes [6] [14] [15] [16].

An alternative interpretation of the battery model proposed by Rakhmatov is presented in [11], which indicates that the deviation from ideal behavior is due to the build up of “unavailable charge”, during the discharge process. If the duration of the rest period is sufficiently large (larger than 30 minutes), the unavailable charge for both policies tends to zero. Based on the above description, by inserting some rest periods, the “unavailable charge” can be restored and we think the battery as ideal energy sources- Linear Time Invariant. The main contributions of these works are as follows:

- Based on the periodic feature of data acquisition in BSN and battery recovery effect, we simplify the battery model.
- Based on the previous simplified battery model, we present local optimization for BSN data transfer.
- Based on the battery recovery effect, we present battery recovery algorithm by inserting idle periodic when transmission finishes.

The remainder of the paper is organized as follows. Section II introduces the background of our work, which includes the analytical battery model, and battery characteristics. Section III describes local optimization scheme along with the simulation results. This paper ends with a conclusion in Section IV

II. BACKGROUND

After designing an energy-efficient communication system to reduce the energy consumption by wireless transmission, a crucial way to further extend the lifetime of battery is battery-aware task-scheduling technique, which can enable the current profile friendly to battery. In this section, we’ll address the problem of batter-aware task-scheduling for BSN nodes.

A. System Configuration

As is shown in Fig.1, the communication node consists of a data acquisition unit, a data processing, a wireless

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transmission and battery management. The data acquisition is used for capturing body information such as image. The data processing is used for data compression and packet data. The compressed data after baseband processing are transmitted to outside by wireless transmission unit. The smart battery supplies power to the three units.

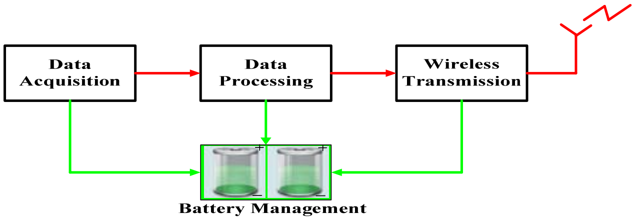

Fig.1 BSN node configuration

B. *Battery Model*

In order to propose a good scheduling algorithm, the non-linear behavior of battery should be well understood. In our work, we use an accurate analytical charge-based model for battery simulation [22]. In this model, the load profile is given in the form of a sequence of *N* constant current values $I_1, I_2, I_3, \ldots\ldots, I_N$, where I_k is the current of task *k* at time t_k, and is applied for a duration $\Delta_k = t_{k+1} - t_k$. The relation between the load profile $\{ I_k, t_k \}$ and the battery's lifetime *L* is as follows:

$$\alpha = \sum_{k=1}^{N} I_k \Delta_k + \sum_{k=1}^{N} 2I_k \sum_{m=1}^{\infty} \frac{e^{-\beta^2 m^2 (L - t_k - \Delta_k)} - e^{-\beta^2 m^2 (L - t_k)}}{\beta^2 m^2} \qquad (1)$$

Where α and β are battery parameters. The parameter α represents the total charge in the battery when it is fully charged. The parameter β measures the nonlinearity of the battery and tells us how fast the diffusion process can keep up with the rate of discharge. The higher the value of β, the better the battery performs. In order to find the battery charge consumption σ after the execution of M tasks (M<N) which run until time T (T<L), we use the following formula obtained from Equation (1) by substituting *N* with *M* and *L* with *T*

$$\sigma = \sum_{k=1}^{M} I_k \Delta_k + \sum_{k=1}^{M} 2I_k \sum_{m=1}^{\infty} \frac{e^{-\beta^2 m^2 T} \times (e^{\beta^2 m^2 \Delta_k} - 1)}{\beta^2 m^2} \times e^{\beta^2 m^2 t_k} \qquad (2)$$

C. *Battery Behavior*

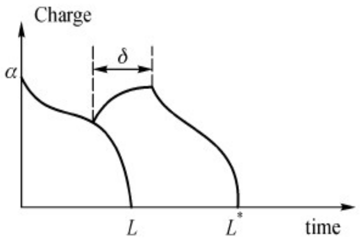

Fig. 2(a) Battery Recovery Effect (δ : rest time)

There are two important properties of the battery used in this paper. The first one is the ability to recover part of the lost charge, referred to as the recovery effect (See Fig. 2(a)).

As the load draws current from the battery, the electroactive species diffuse toward an electrode and a non-zero concentration gradient of the electroactive species develops across the electrolyte. This is the property that is used to increase the battery lifetime at the expense of increase in delay in [6] [8] [14] [15]. When the concentration at the electrode surface falls below a threshold, the battery is said to be cutoff.

Another important property of battery is rate capacity. If the current is reduced from *I* to *I/2*, the battery lasts for a time L_2 which is longer than 2× L_1, where L_1 is the battery lifetime for current I (See Fig. 2(b)). Thus lower the current loads, better the battery performance.

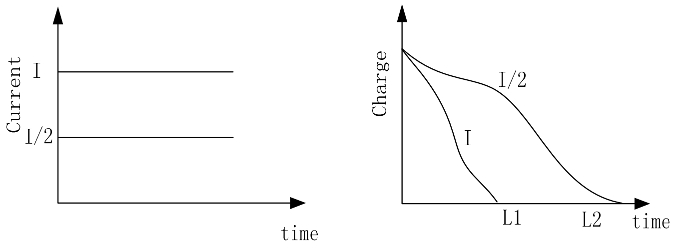

Fig. 2(b) Battery charge non-linearity: Rate capacity effect

D. *BSN Characters*

There are several important characteristics of the BSN nodes and are summarized below and illustrated using examples.

1. Periodicity: The task running in BSN node is usually cyclical, which collects ECG, PPG and other physiological parameters.
2. Predictability: According to the packet size, transmission time can be calculated under certain current conditions.
3. Soft Real Time：The BSN system is generally soft real time，and when transmission fails, the results are not were disastrous.

Based on above BSN characters, we first simply battery model, and then distributes slack time between adjacent tasks.

III. LOCAL OPTIMIZATION FOR SLACK TIME

A. *Simplified battery model*

Some algorithms that tried to minimize charge consumption have been developed by using this cost function this cost function has another useful interpretation in [23].

$$\sigma(t) = \underbrace{\sum_{k=1}^{M} I_k \Delta_k}_{l(t)} + \underbrace{\sum_{k=1}^{M} 2I_k \sum_{m=1}^{\infty} \frac{e^{-\beta^2 m^2 t} \times (e^{\beta^2 m^2 \Delta_k} - 1)}{\beta^2 m^2} \times e^{\beta^2 m^2 t}}_{u(t)} \qquad (3)$$

The first term in (3) is the actual charge lost till time t, which we denote as $l(t)$. The second term is clearly non-negative, or $\sigma(t) - l(t)$.

Let us denote the second term in (3) as $u(t)$. It is clear that this term causes the available charge to be smaller than its ideal value of $a - l(t)$. Hence, this term can be interpreted as the unavailable charge at time t. The unavailable charge $u(t)$

for a given load profile is a monotonically decreasing function of the β parameter and the t, a small value of β (around 0.1 $\mathrm{min}^{-1/2}$) causes significant build up of unavailable charge. We assume

$$F(\beta, t_i, t_f, t) = 2\sum_{m=1}^{\infty} \frac{e^{-\beta^2 m^2 T} \times (e^{\beta^2 m^2 \Delta_k} - 1)}{\beta^2 m^2} \times e^{\beta^2 m^2 t_k} \quad (4)$$

So

$$u(t) = IF(\beta, 0, \Delta, t), t \geq \Delta \quad (5)$$

Obviously, $F(\beta, t_i, t_f, t)$ is monotonically decreasing for t.The maximum unavailable charge $u_{\max} = u(\triangle^{+})$ and the recovery time, $t_r(\varepsilon)$, is defined as that additional time after Δ by which the unavailable charge has reduced to a fraction ε of the maximum unavailable charge

$$IF(\beta, 0, \Delta, \Delta + t_r) = \varepsilon IF(\beta, 0, \Delta, \Delta^{+}) \quad (6)$$

It is difficult to obtain a closed form expression for $t_r(\varepsilon)$ from the above equation. However,

$$e^{-\beta^2 t_r} \sum_{m=1}^{\infty} \frac{1 - e^{\beta^2 m^2 \Delta_k}}{\beta^2 m^2} \geq \sum_{m=1}^{\infty} \frac{e^{-\beta^2 m^2 T} \times (1 - e^{\beta^2 m^2 \Delta_k})}{\beta^2 m^2} \quad (7)$$

And using (6), an upper bound on t_r can be obtained as

$$t_r \leq -\frac{1}{\beta^2} \log(\varepsilon) \qquad (\varepsilon \geq 0.6) \quad (8)$$

The above bound is not tight in most practical cases, and we find the time taken to recover at least 60% of the unavailable charge.

Simplified battery model: after the task set is finished, to $u(t)$ be smaller, we insert $t_r(\varepsilon)$ to restore recover the unavailable charge. When $u(t)$ is close to zero, we can only consider $l(t)$,and $\sigma(t)$ is simplified to $\sigma(t) \approx l(t)$.Using the simplified battery model, we design local optimization for slack time between tasks.

B. *Local optimization for slack time*

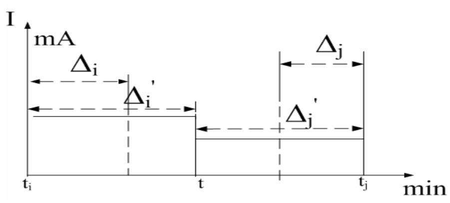

Fig.3. Seek t to minimize consumption charge

Some static task-scheduling algorithms for Battery-Powered DVS Systems [10] are proposed. Because of the complexity of the battery model, several important properties are also developed in [10], and one of the most important principles is that "Given a pair of two identical tasks in the profile and a delay slack to be utilized by voltage downscaling, it is better to use the slack on the later task than on earlier task". However, it is not always the best method that using the slack on the later task.

Local optimization for slack time: We distribute slack time in two adjacent tasks from back packet to front gradually and assume the first packet begins in t_i and the last packet ends in t_j.The execution time to transfer packet is Δ_i, the load current profile is I_i .Fig.3 show the process of local optimization for slack time.

$$\sigma(T) = \underbrace{l_i(T) + u_i(T)}_{\Delta_i} + \underbrace{l_j(T) + u_j(T)}_{\Delta_j} \quad (9)$$

Based on simplified battery model, when inserting $t_r(\varepsilon)$ after *T*.

$$\sigma(T) \approx \underbrace{l_i(T)}_{\Delta_i} + \underbrace{l_j(T)}_{\Delta_j} = I_i \Delta_i + I_j \Delta_j \quad (10)$$

$\sigma(T)$ is the constant charge consumption until T. The local optimization algorithm tries to minimize $\sigma(T)$, where T was the deadline by which the given set of packets was to be completed. The function $I(\Delta_i, \Delta'_i, I_i)$ is the load current profile when transmission time changes from Δ_i to Δ'_i.We choose a fixed packet length L (200 Bytes), and assume the transmission rate to be equal to 10^6 transmissions per second [17]. According to Shannon's channel capacity theorem, we have

$$I'_i = I_i \times \frac{2^{\frac{2}{615\Delta'_i}} - 1}{2^{\frac{2}{615\Delta_i}} - 1} \quad (11)$$

The original transmission time Δ_i and packet current I_i change to the new transmission time Δ'_i and packet current I'_i using local optimization scheme.

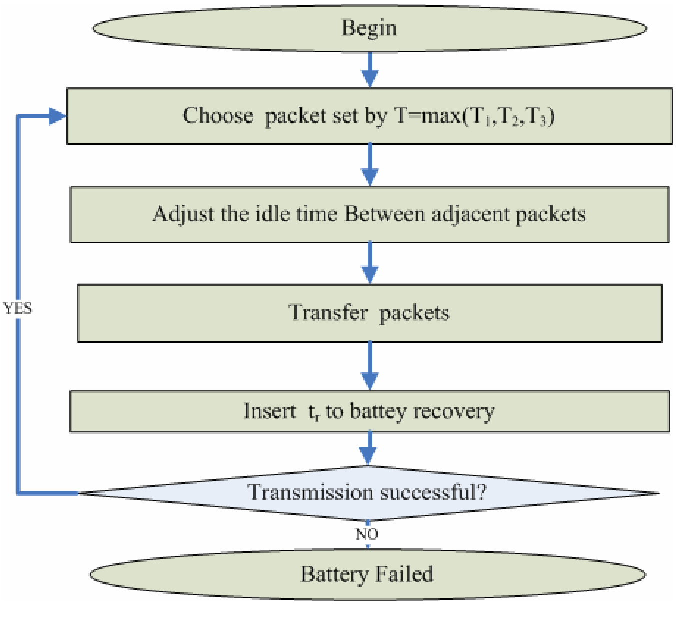

Fig. 4 local optimization scheme for slack time

Therefore, our target for local optimization is

$$\sigma_{\min}(T)=I(\Delta_i,t-t_i,I_i)\Delta_i+I(\Delta_i,t_j-t,I_j)\Delta_j \quad t\in\left[t_i,t_j\right] \tag{12}$$

This problem is a traditional function optimization question of a single variable t. It can be solved by using the bisection method. Based on the above description; below is our algorithm (Fig.4):

1. Calculate the period task $T=\max(T_1,T_2,T_3)$, and we use T as time window.
2. Do local optimization backwards for data packet in the time window.
3. When the task set is finished, inserting time $t_r(\varepsilon)$ for the battery recovery.

C. Simulation Results

In this work, we assume six tasks in buffer as follow

Table I Initial packets queue Specification

Packet	Begin(min)	Duration(min)	Deadline(min)	Current(mA)
1	0	1	40	25
2	2	2	40	30
3	6	2	40	10
4	12	3	40	6
5	17	2	40	12
6	21	1	40	8

Table II gives the progress result after the local optimization. The comparison results is below (α=32768, β=0.876)

Table II shows the effect of local optimization on the battery charge consumption. From the test results, we can conclude that local optimization algorithm reduce about 79% the battery's electric charge consume and extend battery life. The proposed model is simple and easy to implement on the real system.

TABLE II LOCAL OPTIMIZATION THE COMPARISON

Profile	Consumption σ (mA-min)	Residual Q (mA-min)
Non-optimization	2261	30507
Local-optimization	468	32331

IV. CONCLUSION

In this paper, we addressed the packet transmission scheme for battery-operated BSN nodes. First of all, according to important characteristics of the BSN , we simplify the battery model with the consideration of the precision. Furthermore we apply local optimization algorithm to slack time between adjacent packets by inserting idle periodic when transferring is finished. The battery friendly packet transmission scheme is not limited to BSN nodes, but also applied to other wireless sensor nodes.This is the object of our current research.

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