ENERGY-EFFICIENT MULTIPRIORITY MAC OF WIRELESS BODY AREA NETWORK

Zhang Jinbao, Chen Lei

***Abstract*—Wireless body area network (WBAN) is more focused for its various applications in medical, rescue, military and so on. Since such network is mainly based on sensing nodes powered by battery, energy efficiency is of significance. According to current MAC protocols, this paper proposes energy efficient MAC for multi-priority wireless body area network, by optimizing Wake up Radio MAC with cost matrix between energy and delay. Linear optimization for objective cost function leads to energy efficient solution, reducing energy cost by adjusting the probability of commands 'wake_up' and 'sleep' for sensing nodes under giving status.**

***Index Terms*—wireless body area; energy efficiency; MAC; multi-priority;**

I. Introduction

WIRELESS Body Area Network (WBAN) promotes the human as the center of implementation of networking. And it is more focused for its various applications in medical, rescue, military and so on. The international organization for Standardization (ISO) for WBAN set up a special committee of the sixth task force (TG6), responsible for IEEE802.15.6 standards [1].

WBAN is organized with centre of the human body, and sensing nodes are often wearable, and critical sensors tend to be implanted, like medical sensing nodes [2]. So energy supply is key problem. Consequently, energy efficiency of WBAN is more and more focused [3].

Energy consumption of sensing nodes is mainly due to wireless transmissions. Thus current researches are more likely to propose optimal MAC to reduce energy consumption by sleep wireless transmissions while nodes are idle [4].

Current energy efficient MAC proposals are mainly based on hard switch scheme [5, 6]. That is to say, once the sensing nodes complete data transmitting, their wireless components turn to sleep immediately. But it will introduce extra energy consumption in switches between sleep and wake status, also hard switch scheme will introduce extra delay in transmissions.

For example, in WBAN with MAC protocol based on wake-up radio, energy consumption of sensing nodes are of 3mW when active with no wireless transmissions, almost 0mW when sleep, but 4mW and 2s delay when switch between sleep and active. Thus we can conclude that frequently hard switches are not going to be efficient. And it will cause extra delay.

This work presents analysis on such problem in-depth, and builds up a stochastic model based on Markov chains, to improve energy efficiency of MAC in WBAN. The rest of this work is organized as follows. Section II describes the Markov chains based model; section III proposes cost matrix, and linear optimized solutions; section IV presents simulation results; section V concludes this work.

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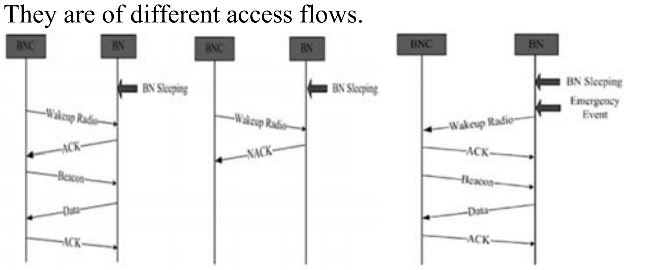
II. Stochastic Model of Multi-priority MAC of WBAN

A. System Model of Multi-priority MAC of WBAN

For simplicity, the example WBAN is consisted of two types of sensing nodes, which are central node (BNC) and edge nodes (BN).

According to the characteristics of data transmissions, data can be divided into two types, periodic and emergency service. They are of different access flows.



(a). for periodic service (b). for emergency service

Fig. 1. Access flows

Periodic service is launched by BNC, waking up BN periodically, as shown in Fig. 1 (a). Emergency service is initiated by BN, when a sudden event occurs randomly and unpredictably, as shown in Fig. 1 (b). Such transmissions are common in medical WBAN applications.

B. Markov Chains Model

BNC issues commands and receives data from BN, and BN generates data, transmitting data, or enter the sleep state according to commands from BNC. Similarly, BN state is defined according to the average number of interval data request in unit time from BNC, and the service rate. Different service rate is corresponding to different states in the node. When the service rate is zero, we call the BN in a dormant state, on the contrary, when the service rate is non zero, we call the active node.

As it is unpredictable when WBAN data generates, arrival of data services and service processes are stochastic process. That is to say, data arrival interval and business hours are random and uncertain. Therefore, the system model is of basic premise: in normal business hours, the volume of business model processing system is not certain [7 - 9].

Sensing nodes contains modules of acquisition, storage, processing and transmission of data. Thus the stochastic model of BN is built on the basis of sequence and module function before and after the node communication process, and it is divided into three parts: service request (SR), queue and service provider (SP), shown as Fig. 1.

SR module is mainly responsible for the acquisition of specific data, and the transmission of data request; queue module is mainly used to store data; SP does simple treatment and then transmit the data to BNC. Data provided by SP is of no priority in data processing requests, that any data requests are no different.

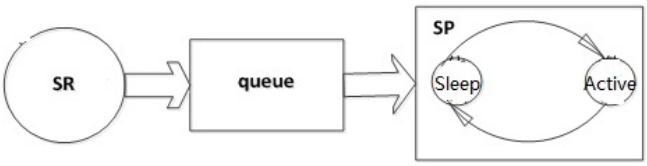


Fig. 1. Markov Chains Model

III. Cost Matrix and Linear Optimization

A. Energy Cost Model

Assume that centralized WBAN with N nodes of 1 BNC and N-1 BNs. Data transmissions are only launched between BNC and BN. Generation of BN data follows Poisson distribution of parameter λ, and that is to say the average time interval of data arrival is $T = 1/\lambda$.

Use E_{avg} to denote the average energy consumption of the sensor node, E_{wk}, E_{tx} and E_{rx} to denote respectively for energy in the wake, data transmission, receiving the data of sensor nodes to consume, and E_{ov} has brought to the extra cost of energy consumption, so we have,

$$E_{avg}=E_{wk}+E_{tx}+E_{rx}+E_{ov} \tag{1}$$

E_{wk} is consisted of two parts, receiving wake-up signal and replying of ACK,

$$E_{wk}=(P_{rwbn}\times T_{wbn}+P_{twack}\times T_{twack})/\mathrm{T} \tag{2}$$

E_{tx} and E_{rx} are respectively,

$$E_{tx}=P_{tx}\times T_{data}/T \tag{3}$$

$$E_{rx}=P_{rx}\times (T_b+T_{ack})/T \tag{4}$$

E_{ov} is composed of control sensor node dormancy, dormancy, switching into receiving/transmitting from sleeping, and switching between transmitting and receiving. Thus,

$$E_{ov}=P_{sl}\times T_{sl}/T+P_{tr}\times T_{tr}/T+2P_t\times T_t/T+P_{wbn}\times T_{wbn}\times (N-1)/T \tag{5}$$

Where, P_{sl}, P_{tr}, P_t and P_{wbn} denote power for the sensor nodes respectively in a dormant state, from dormancy into activated transition between States, receiving data and data transmission state, sending Wake Up Radio signal to BNC. T_{sl}, T_{tr}, T_t and T_{wbn} are used to denote the process time respectively. We also have,

$$T_{sl}=T-T_{tr}-2T_t-T_b-T_{data}-T_{ack} \tag{6}$$

B. Cost Matrix

Definition 1: Solution $\delta^n=\delta(H_n)=\{p_a(H_n)\ \text{s.t.}\ a\in A\}$ is the set of function p_a at time t_n, where $H_n\in[0,1]$, sum of $p_a(H_n)=1$.

For the system information H_n, any determined δ^n is discrete distributed random quantity. The probability of $p_a(H_n)$ corresponds to every command of $a\in A$. On the start of n^{th} time slot, BNC sends command a to control SP in BNs, with the probability of $p_a(H_n)$. And A is probability of distribution, and command sent by BNC is a random selection within A.

Definition 2: Stable solution means that, all the decisions remains same on each time slot t_i (i = 1, 2, 3, …), when $\delta^n=\delta$, where $\pi=[\delta，\delta…)$.

Using stable solution, δ is the function of system status, and that is to say, stability relies on system status of x, unchanging with time. However, stable solution does not mean that BNC must send the same command in every time slot. Probability of distribution A is determined by δ.

Let $\boldsymbol{P}(a)$ denote system transition probability matrix, and $\boldsymbol{P}(a)$ is function of command $a\in A$. So we have,

$$\boldsymbol{P}_{\delta^n} = \sum_{p(a)\in\delta^n} p(a)\boldsymbol{P}(a) \tag{7}$$

In this model, we set command s_on and s_off to control BN. Define $\delta^n=\{p_{s\_on}, p_{s\_off}\}$, where BNC sends command s_on and s_off with the probability of p_{s_on}, p_{s_off} respectively.

Then for a infinite time sequence of [1, 2, …), commands from BNC is modeled as a discrete sequence of $\pi=[\delta^1, \delta^2, …)$. Such sequence proposes solution selected by BNC definitely. So we can define transition matrix for solution π as follows.

$$M_\pi^{\mathrm{T}} = \begin{array}{c} \\ s\_on \\ s\_off \end{array} \begin{array}{c} \begin{array}{cccccccc} x_1 & x_2 & x_3 & x_4 & x_5 & x_6 & x_7 & x_8 \end{array} \\ \begin{bmatrix} 0.4 & 0.2 & 0.5 & 1.0 & 0.4 & 0.8 & 0.8 & 1.0 \\ 0.6 & 0.8 & 0.5 & 0.0 & 0.6 & 0.2 & 0.2 & 0.0 \end{bmatrix} \end{array} \tag{8}$$

Consequently cost matrix of average power consumption is introduced as,

$$\boldsymbol{C}_\delta^{\mathrm{T}} = \left[c(x_1,\delta_{x_1})\quad c(x_2,\delta_{x_2})\quad ...\quad c(x_X,\delta_{x_X})\right] \tag{9}$$

Where, $c(s, a)$ denotes the power consumption when receiving command of a under status of s.

For QoS considerations, cost matrix of transmission delay is also introduced as,

$$\boldsymbol{D}_\delta^{\mathrm{T}} = \left[d(x_1)\quad d(x_2)\quad ...\quad d(x_X)\right] \tag{10}$$

For simplicity, (10) assumes that the time delay equals to the number of SR in queue of BN under status of s, that is $d(x) = q$.

C. Optimal Object Function

The model of whole system is presented by a manipulated Markov chain. Its transmitting probability matrix is $\boldsymbol{P}(a)$, optimized solution is π, row vector $p^{(1)}$ of X dimension denotes the initial probability distribution states of system on the time of t_1, called initial probability. Then following $p^{(n)} = p^{(1)}\boldsymbol{P}_\pi^{n-1}$, probability distribution of system on any time t_n is computed. Based on such computation, expectation of power consumption and transmission delay of the system is quantized as follows,

$$\begin{aligned} E_\pi[\boldsymbol{D}_{\delta^{(n)}}] &= p^{(1)}\boldsymbol{P}_\pi^{n-1}\boldsymbol{D}_{\delta^{(n)}} \\ E_\pi[\boldsymbol{C}_{\delta^{(n)}}] &= p^{(1)}\boldsymbol{P}_\pi^{n-1}\boldsymbol{C}_{\delta^{(n)}} \end{aligned} \tag{11}$$

Within equation (11), optimizations of power $\boldsymbol{C}$ and delay $\boldsymbol{D}$ are coherent. Optimization of $\boldsymbol{C}$ is provided by maximum delay $\boldsymbol{D}$ for the system, so we have optimal object function as,

$$\begin{cases} \mathrm{PO}: \min\limits_{\pi}\left\{ \lim\limits_{N\to\infty}\left(\dfrac{1}{N}\sum\limits_{n=1}^{N} E_\pi[\boldsymbol{C}_{\delta^{(n)}}]\right)\right\} \\ \text{s.t.} \lim\limits_{N\to\infty}\left(\dfrac{1}{N}\sum\limits_{n=1}^{N} E_\pi[\boldsymbol{D}_{\delta^{(n)}}]\right) \le D_{\max} \end{cases} \tag{12}$$

In (12), $N\text{->}\infty$ implies that the observed time span is infinity. For real application, power supply of sensing nodes limited. Consequently optimization is meaningless for an infinite time span. As to this problem, we degrade (12) to a finite window of time N_{finite}. The parameter of N_{finite} is called cut-off time.

We assume that system starts on a certain time slot, and this time slot will continue with probability of β ($0<\beta<1$), or end with probability of β. So finite window of time introduces an extra captured status of x_0 into Markov system. Consequently N_{finite} is of geometric distribution with parameter of β. Its expectation is $E[N]=(1-\beta)^{-1}$.

Thus we can compute the distribution of this system with,

$$p^{(n)} = p^{(1)}(\beta\boldsymbol{P})_\pi^{n-1} = \beta^{n-1}p^{(1)}\boldsymbol{P}_\pi^{n-1} \tag{13}$$

Then object function (12) is rewritten as,

$$\begin{cases} \mathrm{PO}: \min\limits_{\pi}\left\{ \sum\limits_{n=1}^{N_{finite}} E_\pi[\boldsymbol{C}_{\delta^{(n)}}]\right\} \\ \text{s.t.} \sum\limits_{n=1}^{N_{finite}} E_\pi[\boldsymbol{D}_{\delta^{(n)}}] \le D_{\max} \end{cases} \tag{14}$$

(14) is approximate cumulative expectation. Since $0<\beta<1$, $p^{(1)}\boldsymbol{P}_\pi^{n-1}$ is finite, and consequently (14) is convergent.

D. Linear Optimization

Consider PO of (14) without constraints, it is optimized with polynomials to obtain solutions [10]. Optimization without constraints is shown as,

$$\mathrm{POU}: \min_{\pi}\left\{p^{(1)}v_\pi\right\} = \min_{\pi}\left\{\sum_{n=1}^{N_{finite}} \beta^{n-1}p^{(1)}\boldsymbol{P}_\pi^{n-1}\boldsymbol{d}_{\delta^{(n)}}\right\} \tag{15}$$

Reference [7] proposed the solution for (15) as,

$$v_x = \min_{\delta\in\Delta}\{\boldsymbol{d}_\delta + \beta\boldsymbol{P}_\delta v\} \tag{16}$$

Where, Δ is the finite set of all possible stable optimal solutions for X^A.

Then [8] gave the equal linear optimization as follows,

$$\begin{aligned} &\mathrm{LP}: \min\left\{\sum_{x\in X}\sum_{a\in A} f_{x,a}c(x,a)\right\} \\ &\text{s.t.}\left\{\sum_{x\in X} f_{x,a} - \beta\sum_{y\in X}\sum_{a\in A} p_{y,x}(a)f_{y,a}\right\} = p_x^{(1)} \end{aligned} \tag{17}$$

Where, for all x and a, $f_{x,a} \ge 0$.

LP can define $f_{x,a}$, and then optimal solution of $\boldsymbol{M}_\pi$ is computed as,

$$m_{x,a} = f_{x,a} \Big/ \left(\sum_{a'\in A} f_{x,a'}\right) \tag{18}$$

Reference [55] points out that, POU gives stable solution of Markov chains. When the constraints work, the given solution is stochastic stable for this Markov chains.

IV. Simulation and Results

A. Configuration of Simulation

In this paper, Matlab is used to build simulation. WBAN is of a typical star topology. We set up a total of 10 sensor nodes, 9 BNs, and 1 BNC. Distance between neighboring nodes is set to 60-90cm, and the effective transmission distance is 120cm.

In this simulation, we choose the carrier frequency as 2.4 GHz, and modulation as O-QPSK, according to the proposed MAC protocol, services of multi-priority are simulated. Simulation parameters are listed in the following table.

TABLE I
Simulation Parameters

parameter	value	parameter	value
Number of Nodes	10	Power of transmitting	27mw
Data rate	25Kbps	Power of receiving	7mw
Simulation time	100s	Power of switching from sleep to active	4mw
Size of Wake-up packet	8Bytes	Power of working	2mw
Size of ACK packet	8Bytes	Power of transmitting wake-up packet	3mw
Size of Beacon	10Bytes	Power of receiving wake-up packet	1mw
Size of data packet	50Bytes	Power of switching between receiving and transmitting	9mw

B. Results and Analysis

Simulation results are shown in the following Fig. 2.

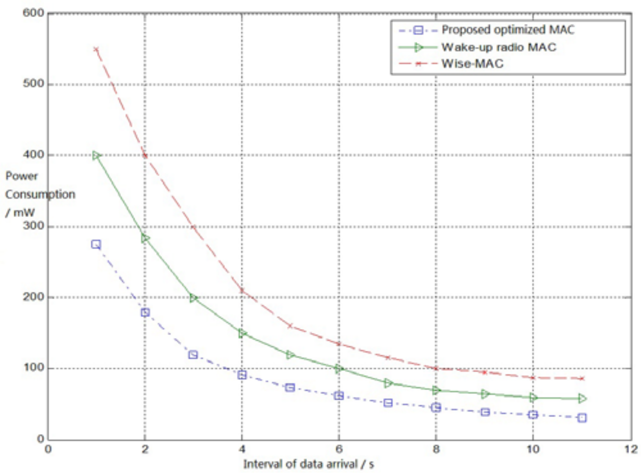


Fig. 2. Simulation Results

In the figure, interval of data arrival indicates the average time interval of Poisson process. And traditional wake-up radio MAC and a improved Wise-MAC protocol [11] are simulated as comparison.

Wake up radio MAC is realized by periodically wakeup signal, eliminate the idle listening on a channel, at the same time the control byte overhead is greatly reduced, avoiding the energy consumption.

While Wise-MAC uses CSMA competition mechanism, not only need the additional overhead, but also listen to the channel continuously, introduce large energy consumption.

It is obviously that, comparing the simulation results, the proposed optimized MAC protocol is of best energy efficiency, with the increase of data arrival interval, and energy consumption for the system gradually decreased.

V. CONCLUSIONS

In view of low energy consumption and low delay requirements for WBAN, this work proposed optimal MAC design of multi-priority service in WBAN. With help of Markoff chains model, the MAC is linear optimized, by solving the objective function to achieve the minimum energy consumption in the delay constraint conditions. Simulation results show that, the optimal solution controls the nodes whether switch dormant or active state in the next moment, avoiding power consumption introduced by state transition between nodes.

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