Adaptive Queue Management Scheme for Body Area Network with Energy Harvesting

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ABSTRACT
There are two important factors for the nodes of Wireless Body Area Network (WBAN): the lasting lifetime and the low loss of significant biometric data. Therefore, the stabilities of both the data queue and the energy queue are an important point on the WBAN nodes. In this paper, Minimum Distance Adaptive Allocation (MDAA) is proposed which is an adaptive queue management scheme to maintain the stabilities of both the data queue and the energy queue. MDAA adjusts the time ratio between energy harvesting and data transmission to minimize the Euclidean distance between the next state and the ideal state. The performance of the proposed scheme is evaluated and takes positive assessments rather than that of the control group.

Categories and Subject Descriptors
C.2.1 [**Computer-Communication Networks**]: Network Architecture and Design—Wireless communication;

General Terms
Design, Algorithms, Performance, Experimentation

Keywords
RF energy harvesting, queue stability, Wireless Body Area Network (WBAN), lifetime, data overflow

1. INTRODUCTION
In these days, we have significantly experienced the expansion of personal digital space and make massive usage of compact devices which interconnect each other through wireless network. In particular, due to the serious population aging and the growing interest in health problems, U-health care service would be one of the most promising applications. One of the most suitable solutions is Wireless Body Area Network (WBAN) to support U-health care service.

Since WBAN nodes are usually attached on or injected into human body for sensing specific symptoms and treating diseases [1], their size should be small and have simple structure. Due to this small scale, WBAN nodes should also have small form factor and battery volume. Also, the battery change of WBAN nodes is very hard work or even impossible to do.

Even if an ultra-low power device which consumes much smaller power than other device is developed, their batteries still have a finite capacity. In order to construct ubiquitous human centric interface, there should be a new idea to surpass the limit of existed researches. For these reasons, energy harvesting technique is deemed to be essential as a self-power generating method [2]. It can also provide a breakthrough which solves the problems related to energy-limited system.

There are some harvestable energy sources in the environment: wind, heat, vibration, solar, thermoelectricity, etc. By using above energy sources, the energy-limited devices can operate without the change of battery. In [2], [3], the reliability and efficiency of ambient energy sources are analyzed. However, the irregular and unpredictable characteristics are the fatal weaknesses of all the environmental energy sources [4]. Therefore, more deterministic and predictable energy source should be needed: energy harvesting using RF signals. Transferring and harvesting wireless signals can be easily controlled so the energy-depleted device can be supplied with the RF energy transfer when the node needs opportunistically [5].

There are some researches on the RF energy harvesting issues. In [6], the analysis of rate-energy region is studied for simultaneous information and power transfer in Multiple Input Multiple Output (MIMO) broadcasting system. The cooperative RF energy transfer scheme with relay nodes is proposed in [7]. The optimal opportunistic spectrum sensing policy in cognitive radio network with energy harvesting is developed in [8].

However, the RF energy harvesting technique also has a drawback. Because of the usage of antenna, the node cannot harvest the energy and transmit the collecting data simultaneously [5]. Therefore, WBAN node should divide the time between energy harvesting and data transmission.

There are two queues in the WBAN node: the data queue and the energy queue. The states of the data queue and the energy queue are changed how the WBAN node determines the time ratio between energy harvesting and data transmission. Not only the long lifetime but also the less loss of collecting human-related biometric data by overflow of the data queue is the important factor to WBAN. Therefore the queue management scheme for the stabilities of both two queues is significant point.

In this paper, Minimum Distance Adaptive Allocation (MDAA) is proposed which is an adaptive queue management scheme to maintain the stabilities of both the data queue and the energy queue. According to the past queue state, we determine the next queue state by deciding the time ratio between energy harvesting and data transmission adaptively. The evaluated performance is better than that of the control group which decides the fixed time ratio without considering the queue state.

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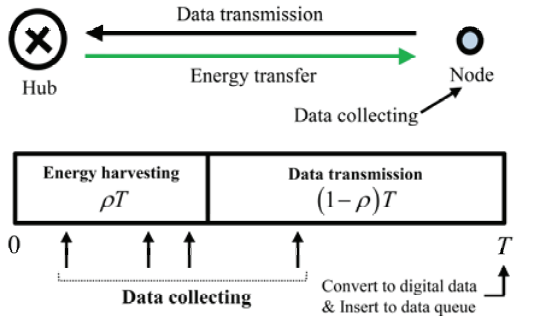

Figure 1. System model and time splitting between energy harvesting and data transmission

2. SYSTEM MODEL

We consider the WBAN consisting of one hub and one node. The hub transfers RF signals which could be converted into the energy and receives the data of the node. On the other hand, the node harvests the RF signals from the hub and performs the data transmission. The size of the data queue and the energy queue is normalized and can be expressed from 0 to 100 which the unit is percentage (%).

As shown in Fig. 1, the node operates energy harvesting and data transmission by splitting each time slot which the length is *T*. The time fraction of energy harvesting and data transmission is ρT and $(1-\rho)T$ respectively. When the node allocates the whole time *T* to the energy harvesting, namely $\rho = 1$, the node can obtain e_h percent of the energy queue. On the contrary, when the node allocates the whole time *T* to the data transmission, namely $\rho = 0$, the node can transmit d_t percent of the data queue and consumed e_t percent of the energy queue.

Moreover, the node also collects the biometric data such as Electrocardiogram (ECG) or Electroencephalography (EEG) signal during the time slot. The collected data during the time slot is converted into digital data and is stored on the data queue at the last moment of the time slot. The stored data occupies d_r percent of the data queue and the corresponding energy is consumed e_r percent of the energy queue. We assume that the quantity of e_r is proportional to the value of d_r.

In summary, d_r, d_t and e_r, e_t, e_h affect the state of the data queue and the energy queue at the next time slot respectively. As shown in Fig. 2, we express the state of the data queue and the energy queue on the two-dimensional coordinate plane for the convenience of our analysis. The residual value of the energy queue and the data queue at the i_{th} time slot are expressed as $x(i)$ and $y(i)$ respectively. The residual value is shown in the percentage, namely $0 \le x(i) \le 100$, $0 \le y(i) \le 100$. The present state of two queues is expressed as position vector $\overrightarrow{p(i)} = (x(i), y(i))$. Then, energy harvesting, data transmission and data collecting can be expressed as two-dimensional vectors. In Fig. 2, the vectors $\vec{e} = (e_h, 0)$, $\vec{t} = (-e_t, -d_t)$ and $\vec{r} = (-e_r, d_r)$ indicate energy harvesting, data transmission and data collecting respectively. The adjustment of the time ratio ρ between energy harvesting and data transmission is the same as deciding the point of internal division of the vectors $\vec{e}$ and $\vec{t}$. Finally, on the two-dimensional coordinate plane, by using the present state of two queues, the time ratio between

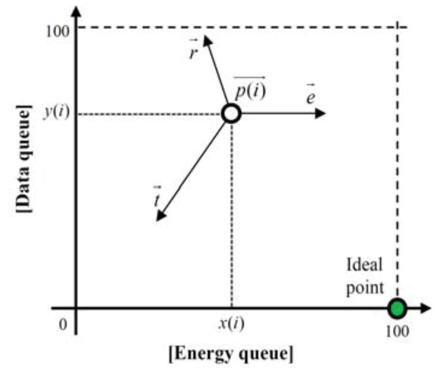

Figure 2. The 2-dimensional space expression of the state of data queue and energy queue

energy harvesting and data transmission and the quantity of data collecting, the state of data and the energy queue at the $i{+}1_{th}$ time slot is expressed as

$$\overrightarrow{p(i+1)} = \overrightarrow{p(i)} + \rho\vec{e} + (1-\rho)\vec{t} + \vec{r}. \tag{1}$$

More specifically, the components of two queues at the $i{+}1_{th}$ time slot are also expressed as

$$\begin{bmatrix} x(i+1) \\ y(i+1) \end{bmatrix} = \begin{bmatrix} x(i) \\ y(i) \end{bmatrix} + \rho \begin{bmatrix} e_h \\ 0 \end{bmatrix} + (1-\rho) \begin{bmatrix} -e_t \\ -d_t \end{bmatrix} + \begin{bmatrix} -e_r \\ d_r \end{bmatrix}. \tag{2}$$

In these circumstances, we consider the stabilities of both the data queue and energy queue. The stabilities of both two queues can be worse by the two events: data overflow and energy depletion. If $x(i)$ gets lower than 0%, the energy queue is depleted. Then the lifetime of node is end. If $y(i)$ exceeds 100%, the data loss of collecting data by data overflow at the data queue occurs. To maintain the stabilities of the data queue and energy queue, we consider how the time ratio between energy harvesting and data transmission is decided.

3. MINIMUM DISTANCE ADAPTIVE ALLOCATION

In this section we introduce the proposed scheme, MDAA. The key concept of the proposed scheme is what the ideal state of the data queue and the energy queue is and how we could make the state of both two queues ideal. Definitely, the data queue and the energy queue are ideal when the data queue is empty and the energy queue is full-charged. On the two-dimensional coordinate plane, the ideal state is expressed as (100,0). Therefore, the proposed scheme decides the time ratio ρ between energy harvesting and data transmission which minimizes the Euclidean distance between the next position $\overrightarrow{p(i+1)}$ and (100,0).

3.1 Problem formulation

An optimization problem in order to obtain the optimal time ratio $\rho*$ can be formulated as:

$$(\mathbf{P1}) \quad \rho* = \arg\min_{\rho} \sqrt{f(\rho)} \tag{3}$$
$$\text{s.t. } 0 \le \rho \le 1,\ 0 \le x(i+1) \le 100,\ 0 \le y(i+1) \le 100,$$

where $\rho*$ is the optimal time ratio and $f(\rho) = (x(i+1))^2 + y(i+1)^2$ for $x(i+1) = x(i) + \rho e_h - (1-\rho)e_t - e_r$, $y(i+1) = y(i) - (1-\rho)d_t + d_r$. Since the square root function is monotonically increasing function, the solution of **(P1)** is the same as the optimal $\rho*$ of minimizing $f(\rho)$. Then, $f(\rho)$ is arranged in descending order of ρ as

$$\begin{aligned} f(\rho) &= (x(i+1)-100)^2 + y(i+1)^2 \\ &= (x(i)+\rho e_h-(1-\rho)e_t-e_r-100)^2+(y(i)-(1-\rho)d_t+d_r)^2 \\ &= \{(e_h+e_t)^2+d_t^2\}\rho^2 \\ &\quad +2\{(e_h+e_t)(x(i)-e_t-e_r-100)+d_t(y(i)-d_t+d_r)\}\rho \\ &\quad +(x(i)-e_t-e_r-100)^2+(y(i)-d_t+d_r)^2, \end{aligned} \tag{4}$$

where d_r, d_t, e_r, e_t and $e_h > 0$. Therefore, $f(\rho)$ is always convex function since the leading coefficient of $f(\rho)$ is always strictly positive $((e_h+e_t)^2+d_t^2>0)$.

3.2 The optimal solution of (P1)

There are three constraints on **(P1)** which is related to ρ. The constraints related $x(i+1)$ and $y(i+1)$ can be arranged as (5) and (6) respectively.

$$\frac{e_h+e_t-x(i)}{e_h+e_t} \le \rho \le \frac{100+e_h+e_t-x(i)}{e_h+e_t} \tag{5}$$

$$\frac{d_t-d_r-y(i)}{d_t} \le \rho \le \frac{100+d_t-d_r-y(i)}{d_t} \tag{6}$$

Then the range of the intersection, **I**, among three constraints is expressed as

$$\begin{aligned} &\mathbf{I} \triangleq \{\rho \mid k_1 \le \rho \le k_2\}, \\ &\text{where } k_1 = \max\left(0, \frac{e_h+e_t-x(i)}{e_h+e_t}, \frac{d_t-d_r-y(i)}{d_t}\right), \\ &k_2 = \min\left(1, \frac{100+e_h+e_t-x(i)}{e_h+e_t}, \frac{100+d_t-d_r-y(i)}{d_t}\right). \end{aligned} \tag{7}$$

If k_1 is larger than k_2, there is no intersection so the optimal ρ^* does not exist. When there is an intersection among three constraints, it means that the optimal solution which minimize the distance between $\overrightarrow{p(i+1)}$ and (100,0) exists.

Since $f(\rho)$ is a quadratic polynomial function which the leading coefficient is strictly positive, the optimal ρ^* can be decided according to the intersection of constraints. If the global minimizer of $f(\rho)$ which can be obtained by using the first derivative is comprised in **I**, the optimal ρ^* is definitely the global minimizer. The first derivative of $f(\rho)$ is written as

$$\begin{aligned} \frac{df(\rho)}{d\rho} &= 2\{(e_h+e_t)^2+d_t^2\}\rho \\ &\quad +2\{(e_h+e_t)(x(i)-e_t-e_r-100)+d_t(y(i)-d_t+d_r)\}. \end{aligned} \tag{8}$$

Then the global minimizer $\rho^{\min}$ is obtained when the first derivative of $f(\rho)$ is equal to 0 and is expressed as

$$\rho^{\min} = -\frac{(e_h+e_t)(x(i)-e_t-e_r-100)+d_t(y(i)-d_t+d_r)}{(e_h+e_t)^2+d_t^2}. \tag{9}$$

If the global minimizer of $f(\rho)$ does not exist in range **I**, the optimal ρ^* is supposed to upper or lower bound of the range **I** which minimize the objective function $f(\rho)$. Finally, the optimal solution ρ^* can be expressed as

$$\rho^* = \begin{cases} \rho^{\min} & \rho^{\min} \in \mathbf{I} \\ \min(f(k_1), f(k_2)). & \text{Otherwise} \end{cases} \tag{10}$$

According to the present position $\overrightarrow{p(i)}$, the optimal time ratio ρ^* to minimize the Euclidean distance between $\overrightarrow{p(i+1)}$ and (100,0) can be determined adaptively.

4. SIMULATION RESULTS

We evaluate the proposed scheme in the view of the stabilities of both the data and the energy queue. The stabilities of both two queues can be measured by lifetime and data overflow. The performances of the proposed scheme are compared with the control group, namely Deterministic Allocation (DA). DA decides the fixed time ratio ρ at the all states of both two queues.

4.1 Simulation parameters

For the simulation, we take the specific value of vectors $\vec{e}=(e_h,0)$, $\vec{t}=(-e_t,-d_t)$ and $\vec{r}=(-e_r,d_r)$. We assume that d_r is a discrete Poisson random variable with mean λ. As aforementioned, e_r is proportional to d_r that the proportionality constant is assumed 0.3. d_t and e_t are chosen as 16 and 22 respectively. We assume that e_h is equal to e_t and the transferred energy should pass through the Rayleigh fading channel which has zero mean and unit variance. The unit of d_r, d_t, e_r, e_t and e_h is percentage so the value can be from 0 to 100. Lifetime can be measured by checking the state of the energy queue depleted. When the state of the data queue exceeds 100%, the data overflow happens.

We simulate and calculate the average value of lifetime and data overflow of both the proposed scheme MDAA and the control group DA with 10^5 iterations. The fixed time ratio ρ of DA is changed from 0.1 to 0.9. We also change the mean of d_r at a step of 0.5 from 11 to 13. The initial point of the state of the data queue and the energy queue is randomly selected on the feasible range $(0 \le x(1) \le 100, 0 \le y(1) \le 100)$.

4.2 Performance evaluation

Fig. 3 and Fig. 4 show the performance of lifetime and data overflow of MDAA and DA respectively. When Fig. 3 or Fig. 4 is analyzed separately, the performance of DA can be better than that of MDAA. For example, when $\lambda = 11$ and ρ is 0.7, 0.8 and 0.9, the lifetime of DA is better than that of MDAA. Also, there are some cases when the data overflow occurred more on MDAA than DA. However, the separate analysis of two performance metrics is not reasonable. Because MDAA takes into account the stabilities of both the data queue and the energy queue, we should analyze lifetime and data overflow simultaneously. On the other hand, even if DA has outstanding performance on lifetime at the specific simulation parameter, DA has remarkably poor quality on data overflow at the same experiment and vice versa because of the fixed time ratio ρ. To sum up, DA has biased performances but MDAA shows well-balanced measurements on both two metrics. For a simultaneous analysis of lifetime and data overflow, Fig. 5 shows the performance plane which x axis and y axis mean normalized lifetime and data overflow respectively. The left 4 figures of Fig. 5 are full range plot and the right 4 figures take an expansion at top right-hand corner. It can be analyzed that the closer the point is to the top right-hand corner, the better performance that point means. Therefore, MDAA is analyzed better performance than DA on both lifetime and data overflow.

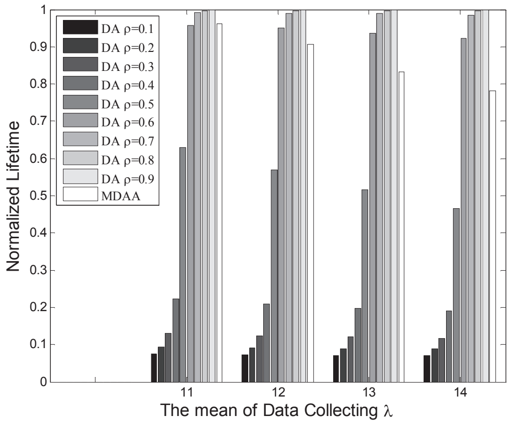

Figure 3. The normalized lifetime of MDAA and DA

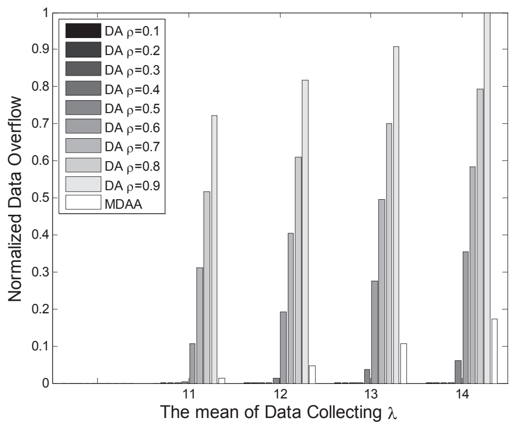

Figure 4. The normalized data overflow of MDAA and DA

5. CONCLUSIONS

In this paper, we proposed the adaptive queue management named MDAA. We modeled the state of the data and the energy queue on the 2-dimensional coordinate plane. Then, MDAA decides the time ratio ρ to minimize the Euclidean distance between the next position of both data and the energy queue and the ideal state. The performance of MDAA was analyzed on lifetime and data overflow and is compared with DA. The analysis was done on the performance plane for a simultaneous analysis of lifetime and data overflow. Simulation results show that MDAA has well performance on lifetime and data overflow evenly.

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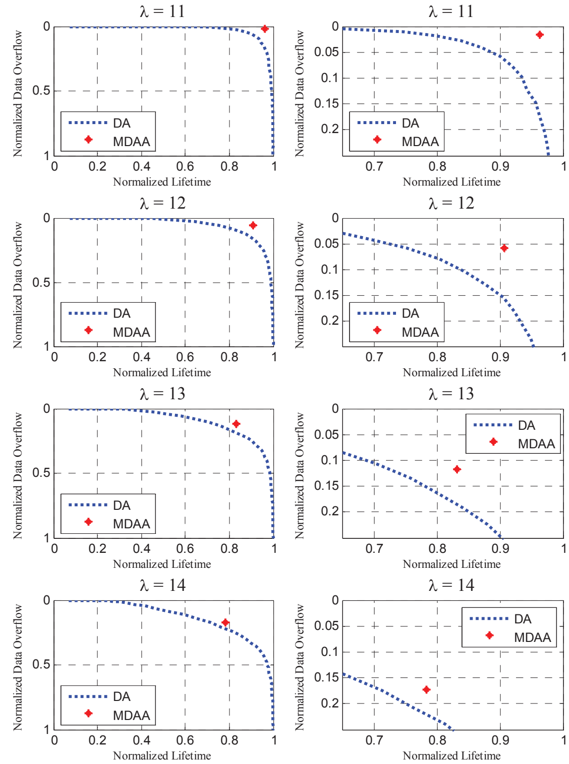

Figure 5. The comparison between MDAA and DA on the performance plane

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