ON THE DESIGN OF AN ENERGY-EFFICIENT DATA COLLECTION SCHEME FOR BODY AREA NANONETWORKS

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ABSTRACT

With the recent advancements in nanotechnologies, Body Area Nanonetworks (BANNETs) are expected to be a promising solution for many critical biomedical applications. Due to the extremely small size of nano-machines, serious energy limitation becomes a challenging roadblock stunting the development of BANNETs. As an initial step towards this end, this paper focuses on the design of an energy-efficient data collection scheme in BANNETs. First, a sleep/wake-up mechanism is introduced to avoid the unnecessary energy consumption when no external request comes. Then, with a careful consideration of both node available energy and transmission energy consumption, we design a new node selection strategy to further reduce the energy consumption in the data collection process. Finally, we conduct extensive simulations for both the proposed data collection scheme and the benchmark greedy scheme to illustrate the energy efficiency of our scheme as well as to discuss the impacts of network parameters on network performance..

KEYWORDS

Body Area Nanonetworks, data collection, energy-efficient, wake-up, node selection

1. INTRODUCTION

The rapid development in nanotechnologies over the last two decades promotes the manufacturing of nano-machines like nano-sensors, nano-actuators and nano-processors [1, 2, 3, 4, 5], which further facilitates the application of Body Area Nanonetworks (BANNETs) [6]. The BANNETs, a kind of the general Wireless Body Area Network (WBAN) architecture [7], can be defined as a collection of nano-machines attached on or implanted in human body which have the capability of communicating with each other. The BANNETs are expected to be an appealing solution for many critical applications in the field of biomedicine, such as health monitoring, genetic engineering, immune system support and drug delivery systems [6, 7, 8, 9]. To support the application and commercialization of BANNETs, designing efficient operations for such networks is of great importance [10, 11, 12, 13, 14].

It is worth noting that, however, the nano-machines in a BANNET are limited in size (usually from 1 *nm* to 100 *nm*), leading to the fact that the energy supplying devices are difficult to be utilized, and thus BANNETs suffer from seriously limited energy constraints which has become a roadblock stunting their further development. As a result, the operations in a BANNET should be carefully designed in an energy-efficient way such that we can extend the lifetime of the BANNET as much as possible. By now, a number of research efforts have been devoted to the design of energy-efficient operations in the general WBANs. For instance, Okundu *et al.* [15] proposed a MAC protocol which applies the single-hop communication and centrally controlled

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wake-up/sleep times to reduce the energy consumption for WBANs. Following this line, the energy-efficient MAC protocols were further explored for WBANs with the star network topology and the master–slave-based network topology in [16] and [17], respectively. In [18], Chi *et al.* constructed the prefix-free codes to minimize the transmission energy consumption with a guaranteed throughput for wireless nano-sensor networks.

To the best of our knowledge, the concept of BANNETs which specifies the general WBANs under the nano-scale began to emerge in the recent four years [6, 19, 20, 21, 22, 23, 24], thus the study on the design of energy-efficient operations for BANNETs is largely uninvestigated. In particular, the data collection scheme, a key component of the energy consumption in BANNETs, should be carefully addressed. Piro *et al.* [24] proposed an initial greedy scheme for collecting physiological data of human body, and it is expected that there still remains huge room for the improvement of data collection. Moreover, we notice that the path loss issue during the data collection process is usually neglected in previous studies. However, the path loss actually influences the energy consumption for a target nano-node transmitting data to its corresponding nano-router (since the path loss significantly impacts the quality of the collected data), and thus it should be carefully addressed.

Motivated by these observations, this paper aims at taking a step forward in the design of energy-efficient data collection scheme for BANNETs. Specifically, we consider a practical BANNET with the transmission path loss and a hierarchical network architecture which consists of nano-interfaces, nano-routers and nano-nodes. For such a BANNET, we first apply a wake-up mechanism to activate the nano-nodes within a specific region of a nano-router when data request happens (the nano-nodes without the region keep the sleep state for saving the energy). We then design the node selection strategy which utilizes the estimated remaining energy after the data collection process (rather than the current energy before the data collection process in [24]) as the metric to select the nano-node from which the data be collected, for prolonging the lifetime of the BANNET as well as improving the data transmission quality.

The main contributions of this paper can be summarized as follows:

- For saving the unnecessary energy consumption, we first introduce a wake-up mechanism to make all nano-nodes in the BANNET keep sleep when there is no external request, while only activate the nano-nodes within a specific region of a nano-router when external request comes.
- In order to further reduce the energy consumption in data collection process, we carefully design a nano-node selection strategy to select the target node with the maximal remaining energy after it executing the data sensing and transmission operations, rather than that with the maximal current energy.
- We conduct network simulations for both the energy-efficient data collection scheme and the benchmark greedy scheme, to demonstrate the energy efficiency achieved by our proposed scheme as well as illustrate the impacts of network parameters on network performance.
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The rest of this paper is organized as follows. Section 2 introduces the system models involved in this study. We present the details of designing the energy-efficient data collection scheme in Section 3. Section4 conducts performance evaluation and Section 5 provides simulation results as well as corresponding discussions. Finally, we conclude this work in section 6.

2. SYSTEM MODELS

This section presents the system models and main notations involved in this paper.

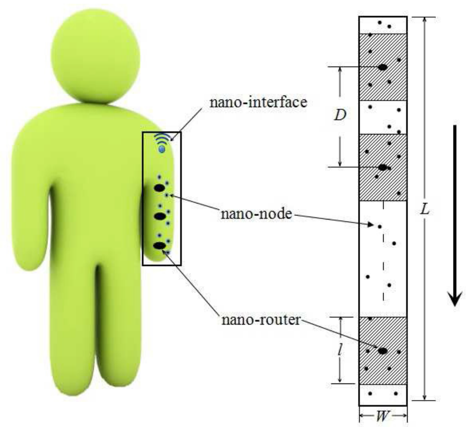


Figure 1. Illustration of system model

As illustrated in Figure 1, we consider a BANNET distributed along the artery of a human arm, which is assumed to be a rectangle area with length L and width W. The network consists of one nano-interface, n nano-routers vertically placed at a mutual distance D, and multiple nano-nodes with density μ. The nano-interface and nano-routers are assumed to be static, whereas all nano-nodes move at a constant speed along the artery following the direction of the blood [25]. The network area is assumed to have torus boundaries such that when a nano-node reaches a boundary, it will move across the boundary and appear in the opposite side. The communication between different nano-machines is over the electromagnetic waves in terahertz band [26, 27, 28]. Through receiving the requests and commands from external entities, this network is able to perform various in-body tasks, like health monitoring, disease detection and drug release.

We assume that all nano-nodes adopt energy-harvesting techniques to continuously gain extra energy supply. Despite the continuous energy supply, operations of nano-nodes (e.g., sensing, receiving request and sending data) will consume their energy. The amount of consumed energy and harvested energy of nano-nodes will be introduced in Section 4 in detail. According to the amount of available energy, each nano-node can alternate on three states, namely, sleep state, active state and invalid state as follows:

- Sleep state: the nano-node keeps sleeping and will not do any operations on this state.
- Active state: when a request from a nano-router arrives at the nano-node, it will turn into active state from sleep state to perform the related tasks. After completing the task, it will automatically turn back to the sleep state.
- Invalid state: when the energy level of the nano-node falls below some threshold E_{th}, it will become invalid and cannot participate in any operation until its energy exceeds E_{th} again through the energy harvesting. The value of E_{th} will be given in Section 4.

It should be pointed out that energy consumption only happens when a nano-node is on the active state, while energy can be harvested no matter which state the nano-node is on the sleep state or active state. We assume that when there is no data request from the nano-routers, all the nano-nodes prefer to stay on the sleep state to save energy.

The main notations of this paper are summarized in Table 1.

Table 1. Main notations

Symbol	Definition
M_r	size of request message
M_a	size of the activation message
M_e	size of the energy feedback message
M_s	size of the answer message
E_{btx}	energy required to transmit a pulse
E_{brx}	energy required to receive a pulse
$E_{tx}(x)$	energy required to transmit a packet of x bits
$E_{rx}(x)$	energy required to receive a packet of x bits
E_{fb}	energy consumed for a nano-node transmitting the feedback message
E_{ans}	energy consumed for a nano-node transmitting the answer message
E_{full}	fully charged energy for nano-node
E_{th}	energy threshold
E_a	available energy for a nano-node
V_{cap}	total capacitance of the ultra nano-capacitor
n_c	number of compress-release cycles
V_g	generator voltage
ΔQ	harvested charge per cycle
A_s	spreading loss
A_{abs}	molecular absorption loss
$K(f)$	absorption coefficient
L	length of the rectangular area
W	width of the rectangular area
D	distance between nanorouter
l	length of wake-up region
d	distance between nano-node and nano-router
α	energy consumption exponent
λ	arrival rate of the external requests to the nano-interface
f	frequency of the electromagnetic waves
μ	density of nano-nodes

3. DESIGN OF DATA COLLECTION SCHEME

In this section, we elaborate the details of designing the energy-efficient data collection scheme, which consists of the hierarchical collection processes from nano-nodes to nano-routers and from nano-routers to nano-interface. Compared with the previous study [24], since we consider the more practical BANNET scenario with the transmission path loss, the proposed scheme is specially designed with a wake-up region, as well as the nano-node selection strategy that selects the node with the maximal remaining energy after it executing the data sensing and transmission operations, rather than the node with the maximal current energy before the data collection process, for improving the energy efficiency.

3.1. Basic Definitions

In order to state the data collection scheme clearly, we first define the following messages:

- Request message: the *request message* is used to indicate what kind of data the external entity is requesting. We use M_r to denote the size of a request message.
- Activation message: the *activation message* is used to change the state of a nano-node from the sleep state to the active state. We use M_a to denote the size of a activation message.
- Feedback message: the *feedback message* is used to indicate the location and the available energy level of a nano-node. We use M_e to denote the size of a feedback message.
- Answer message: the *answer message* is used to contain the information which is requested by the external entity (e.g., the presence of glucose in blood, cholesterol, and infectious agents). We use M_s to denote the size of an answer message.

3.2. Wake-up Mechanism

As mentioned before, in our energy-efficient data collection scheme, we first introduce a wake-up mechanism for saving the unnecessary energy consumption. Notice that the nano-nodes do not execute any operation when there is no external request, thus the mechanism makes all the nano-nodes in a BANNET keep on sleep state during this period (the nano-nodes under the greedy scheme [24] are always on the active state), which will greatly improve the energy efficiency of a BANNET, especially in the case of small external request rate.

Once the the nano-interface receives a request message from the external entity, it forwards this message to all the nano-routers and each nano-router broadcasts an activation message to the nano-nodes in a rectangle region centered at itself with length l and width W, i.e., the dashed area around each nano-router as illustrated in Figure 1. Since we consider a BANNET distributed along the artery of a human arm, of which the width is quite small, in the wake-up mechanism we let the wake-up region only varies in length. We call this region the wake-up region hereafter. This activation message is to activate all the available nano-nodes (the nano-nodes which are not on the invalid state) in the wake-up region and ask them to return the feedback message to their corresponding nano-router, while the nano-nodes outside this region cannot receive the activation message and still remain on the sleep state.

It is worth noting that the wake-up mechanism actually reduces the set of feasible nano-nodes which could be selected as the target node for data sensing and transmission. Except for saving the energy consumption of nano-nodes outside the wake-up region returning feedback messages, this mechanism also naturally reduces the energy consumption for data collection from a target nano-node to its corresponding nano-router. This is because that the expected distance between a target nano-node and its nano-router with the wake-up mechanism is shorter than that without the mechanism, and the energy consumption of data transmission is positive correlated with the transmission distance due to the path loss.

3.3. Nano-node Selection Strategy

By executing the wake-up mechanism, each nano-router can collect the feedback messages from all available nano-nodes in its wake-up region. Based on these feedback messages, the nano-router then applies the nano-node selection strategy to decide which nano-node should be selected as the target node for sensing and transmitting the required data.

With the greedy scheme in previous work [24], the nano-router will select the nano-node with the maximal energy as the target node. However, under the practical BANNET scenario with the transmission path loss, the greedy scheme is not applicable because that the nano-node with the maximal energy could be very far away from the nano-router and this will cause huge energy consumption for data transmission. In order to improve the energy efficiency of the data collection scheme, we carefully design the nano-node selection strategy based on the combination of following two considerations: the current available energy of the nano-node (before it executes the data collection process), and the estimated the energy consumption for this node transmitting the required data.

It is worth noting that the feedback message in our data collection scheme is well designed, which enables the nano-router directly obtain the current energy level of each possible nano-node, as well as estimate the energy consumption for each nano-node transmitting the required data according to the corresponding location information (the estimation of energy consumption will be presented in Section 4). Then our nano-node selection strategy utilizes the estimated remaining energy after the data collection process as the metric (i.e., the difference between the current energy and the estimated energy consumption), to select the nano-node with the maximal value of the metric as the target nano-node for executing further operations.

4. PERFORMANCE EVALUATION

In this section, we conduct theoretical performance evaluation for the proposed data collection scheme in terms of its average available energy in each nano-node and average path loss of each data collection process. The average available energy is used to measure the energy consumption of the BANNET and the average path loss is used to measure the quality (reliability) of the collected data.

4.1. Average Available Energy

We let E_{btx}, E_{brx}, $E_{tx}(x)$, and $E_{rx}(x)$ denote the energy required to transmit a pulse, receive a pulse, transmit a packet of x bits, and receive a packet of x bits to a unit distance of 1 *mm*, respectively. We adopt the Time Spread On-Off Keying (TS-OOK) modulation scheme, where in transmitting a message the presence of a pulse for a specific duration represents a bit 1 while the absence represents a bit 0 [29]. With the TS-OOK modulation, the probability that a collision occurs between femtosecond-long pulses is very low. Due to the fact that the time interval between transmissions is much longer than the pulse duration, several nano-nodes can concurrently use the channel without affecting each other. As in [29], the TS-OOK modulation is configured with the pulse duration, pulse time inter-arrival, and transmission range equal to 100 *fs*, 100 *ps*, and 10 *mm*, respectively, and $E_{btx} = 1$ *pJ* and $E_{brx} = 0.1$ *pJ*. It is worth noting that the transmitter will consume its energy only when it transmits a pulse (i.e., bit 1), while the receiver should consume its energy whenever it receives a bit 1 or bit 0. Thus, the energy required to transmit a message of x bits can be written as:

$$E_{tx}(x) = x \cdot \beta \cdot E_{btx} \tag{1}$$

and the energy required to receive a message of x bits can be written as:

$$E_{rx}(x) = x \cdot E_{brx} = 0.1 \cdot x \cdot E_{btx} \tag{2}$$

Where β is the probability that the bit 1 occurs (generally, β is set as 0.5 because symbols are equiprobable).

We let E_{fb} and E_{ans} denote the amount of energy consumption of a nano-node transmitting the feedback message, and the amount of energy consumption of a nano-node transmitting the answer message, respectively. Then according to [30], we have

$$E_{fb} = E_{rx}(M_a) + E_{tx}(M_e) \cdot d^{\alpha} \tag{3}$$

$$E_{ans} = E_{rx}(M_r) + E_{tx}(M_s) \cdot d^{\alpha} \tag{4}$$

where M_a, M_e, M_r and M_s denote the size (in bits) of activation message, feedback message, request message and answer message, respectively, d is the distance between the nano-node and the corresponding nano-router, α is the energy consumption exponent.

The energy threshold E_{th} is defined as the amount of energy required to complete the request/response mechanism (below which the nano-nodes become invalid). Then E_{th} is determined as

$$E_{th} = E_{fb} + E_{ans} \tag{5}$$

Regarding the energy harvesting of nano-nodes, the conventional mechanisms, e.g., solar energy, wind power, are not feasible in the nano-scale due to the technology limitations [31]. A pioneering mechanism to power nano-sensor motes is to harvest vibrational energy by exploiting the piezoelectric effect of ZnO nano-wires [32]. A piezoelectric nano-generator, consists of an array of ZnO nano-wires, a rectifying circuit, and a ultra-nano-capacitor. When the nano-wires are bent or compressed, an electric current is generated between the ends of the nano-wires. This current is used to charge the capacitor. When the nano-wires are released, an electric current in the opposite direction is generated and used to charge the capacitor after proper rectification. The compress-release cycles of the nano-wires are created by an external energy source, such as air conditioning, heartbeat, and so on. Since we focus on a BANNET, we assume that the heartbeat represents the only energy source.

In [31], an analytical model for piezoelectric nano-generators has been already developed. The voltage V_{cap} of the charging capacitor can be computed as a function of the number of compress-release cycles n_c as follow:

$$V_{cap}(n_c) = V_g\left(1 - \exp\left(-\frac{n_c \Delta Q}{V_g C_{cap}}\right)\right) \tag{6}$$

Where C_{cap} is the total capacitance of the ultra-nano-capacitor, V_g is the generator voltage and ΔQ is the harvested charge per cycle, which is determined by the nano-wire array. Considering the technological constraints of nano-machines, typical values of such quantities are determined as $C_{cap} = 9\ nF$, $\Delta Q = 6\ pC$, and $V_g = 0.42\ V$ [31]. Hence, the energy harvested by one nano-node in its capacitor E_{cap} can be computed as a function of the number of cycles n_c. Then we have

$$E_{cap}(n_c) = \frac{1}{2} C_{cap} V_{cap}^2(n_c) \tag{7}$$

Where C_{cap} is the total capacitance of the ultra-nano-capacitor and V_{cap} is computed from (6).
Figure 2 shows how the amount of energy harvested by a nano-node in a BANNET varies with the number of compressed-release cycles. We can see from Figure 2 that for a nano-node in a BANNET, its fully charged energy E_{full} is about 800 pJ. Hence, we set that all the nano-nodes are fully charged (800 pJ) when the network is initially built in the human body. Thus, the available energy for a nano-node in the BANNET $E_a(T)$ after the network runs T time units (generally in second) from the beginning can be formulated as

$$E_a(1) = E_{full} - 1_{fb}(1) \cdot E_{fb} - 1_{fb}(1) \cdot 1_{ans}(1) \cdot E_{ans} + E_{cap}(1) \tag{8}$$

$$E_a(T) = E_a(T-1) - 1_{fb}(T) \cdot E_{fb} - 1_{fb}(T) \cdot 1_{ans}(T) \cdot E_{ans} + E_{cap}(T) \qquad T = 2,3,\cdots \tag{9}$$

Where $\mathbf{1}_{fb}(T)$ and $\mathbf{1}_{ans}(T)$ are the indicator variables which equal to 1 if the nano-node transmits the feedback message and answer message during the *T-th* slot, respectively, otherwise they equal to 0. $E_{cap}(T)$ denotes the energy harvested during the *T-th* slot. Here, we assume that the compress-release process of the nano-wire in the nano-node occurs one time per second as the heartbeat represents the energy source.

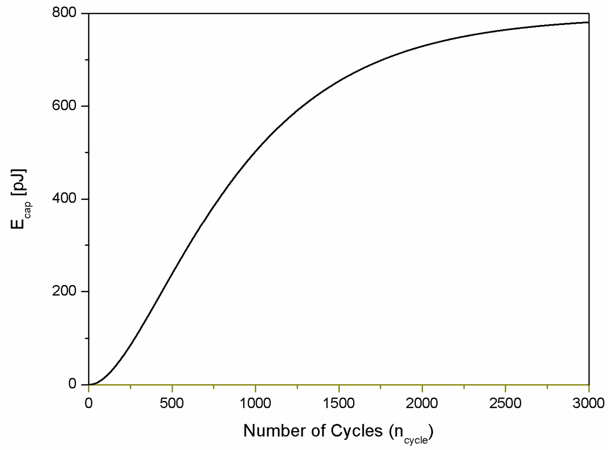


Figure 2. Energy harvested in the ultra-nano-capacitor as a function of the number of cycles.

4.2. Average Path Loss

We let A (in *dB*) denote the path loss of a traveling wave in the terahertz band, which is the sum of spreading loss A_s and molecular absorption loss A_{abs} [33]. Then we have

$$A(f,d) = A_s(f,d) + A_{abs}(f,d) \tag{10}$$

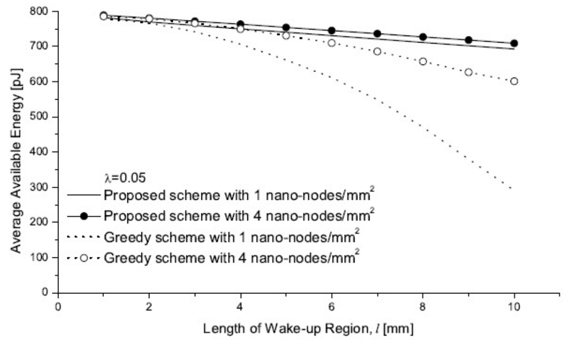
$$A_s(f,d) = 20\lg(4\pi fd/c) \tag{11}$$

$$A_{abs}(f,d) = k(f)d10\lg e \tag{12}$$

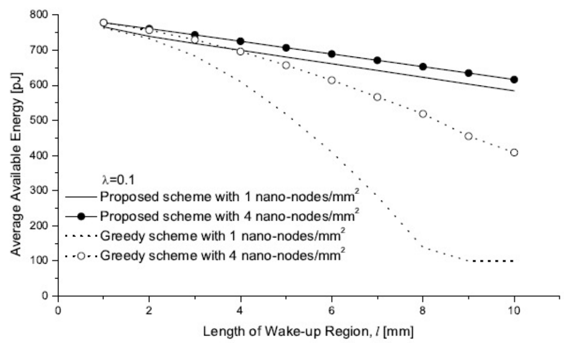
Where d is the path length, f is frequency of the electromagnetic wave, $k(f)$ is the absorption coefficient and c stands for the speed of light in the vacuum. Combining (10), (11) and (12), we can get the path loss of selected nano-node. It should be pointed out that in the terahertz band, the spreading loss is considerably large, limiting the maximum transmission range. However, we consider the extreme path loss observed for such transmission distances, which is mainly affected by molecular absorption in the human body. This is due to the fact that the blood is mainly made up of water.

5. Simulation Results And Discussions

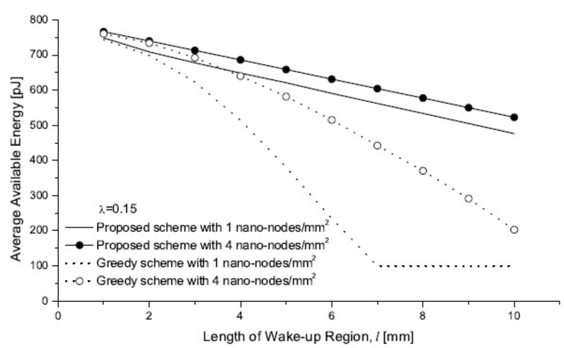
In this section, we conduct extensive network simulations to illustrate the performance of the proposed data collection mechanism in a BANNET, and also discuss the impacts of network parameters on the average available energy and average path loss. As a benchmark scheme, the greedy scheme proposed in [24] is also simulated under the more practical BANNET scenario with the consideration of path loss, to demonstrate the network performance improvement brought by the proposed scheme.



(a) arrival rate of external requests $\lambda = 0.05$

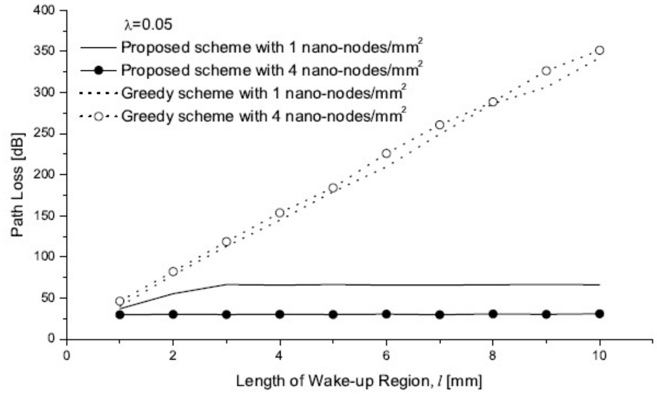


(b) arrival rate of external requests $\lambda = 0.1$

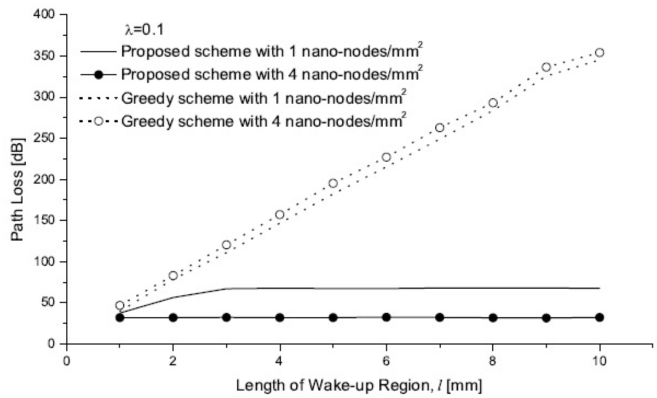


(c) arrival rate of external requests $\lambda = 0.15$

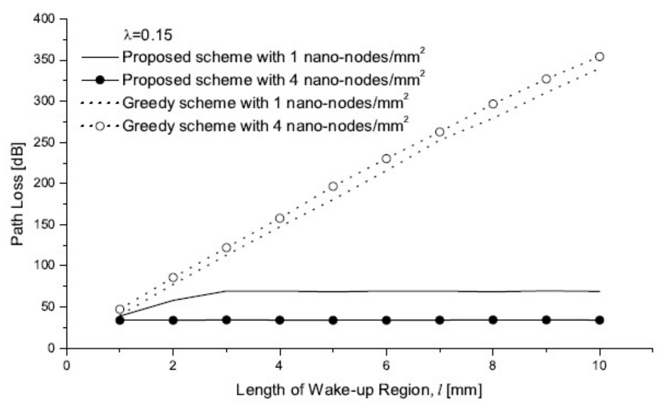
Figure 3. Simulation results for the performance of average available energy



(a) arrival rate of external requests $\lambda = 0.05$



(b) arrival rate of external requests $\lambda = 0.1$



(c) arrival rate of external requests $\lambda = 0.15$

Figure 4. Simulation results for the performance average path loss

5.1. Simulation Settings

For illustrating the performance of the proposed data collection scheme, we developed a dedicated C++ simulator to simulate the external request generation process, movement of nano-nodes and the data collection process in a BANNET. We set the network length L = 300 *mm*, width W = 1 *mm* and place 10 nano-routers with mutual distance D = 30 *mm* in the whole network area. Moreover, similar to the settings in [24], the blood speed is set to be 20 *cm/s*, the size of messages exchanged within the BANNET is set as $M_a = M_e$ = 48 bits and $M_r = M_s$ = 96 bits. Due to the fact that blood is mainly made up of water, we set the electromagnetic frequency is 300 *GHz*, and the absorption coefficient is 123 cm^{-1} [34]. Other network parameters are set as follow: the nano-node density μ = {1, 4} per mm^2, the arrival rate of external requests λ = {0.05, 0.10, 0.15} per slot, and the length of wake-up region l ranges from 1 *mm* to 10 *mm*. It should be pointed out that in order to conduct a more suitable comparison between the two schemes, we also introduce the wake-up region into the greedy scheme, and while the original greedy scheme can be regarded as the case that l tends to L.

5.2. Simulation Results

First, we explore the performance of energy consumption of the proposed data collection scheme, and provide plots in Figure 3 that how the average available energy varies with the length of wake-up region l under various settings of external request arrival rate and nano-node density. In general, we can see from Figure 3 that the average available energy of the proposed data collection scheme is higher than that of the greedy scheme under all the cases, indicating that the proposed scheme can improve the performance of a BANNET in the sense that it reduces the energy consumption. More specifically, we can see that as the length of wake-up region l increases, the average available energy under all the cases decreases, and thus the energy of the original greedy scheme serves as a lower bound for that of the proposed scheme. This is due to the fact that the larger wake-up region, the more nano-nodes would be activated and send feedback message, resulting in more energy consumption.

Moreover, it is worth noting that although both schemes are executed under the scenario with wake-up region, our scheme still outperforms the greedy scheme. This is because that our scheme will select the nano-node with the maximal estimated energy after transmitting the answer message, while the greedy scheme will select the nano-node with the maximal available energy before transmitting the answer message. Figure 3 also shows the impacts of other key network parameters on the energy performance of a BANNET. We can observe that a higher external request rate (a larger λ) will lead to less average available energy (more energy consumption), while the average available energy can be improved by increasing the nano-node density, especially for the scenario with a larger λ.

We further investigate the quality of the collected data of the proposed scheme. To this end, we summarize in Figure 4 that how the average path loss varies with the length of wake-up region l under various settings of external request arrival rate and nano-node density. As illustrated in Figure 4, we can see that the average path loss of the proposed scheme is much lower than that of the greedy scheme under all the cases, indicating that the proposed scheme can improve the quality of the collected data in a BANNET. It is worth noting that as l increases, the average path loss of the greedy scheme increases, indicating that the path loss of the original greedy scheme serves as an upper bound (i.e., the worst quality of the collected data) for that of the scheme with the wake-up mechanism.

A more careful observation of Figure 4 shows that as l increases, the average path loss of the greedy scheme increases linearly, while that of the proposed scheme increases a little and keeps almost constant. This is because the greedy scheme will select the nano-node with the maximal available energy and this nano-node would appear in any location of the wake-up region, thus the expected distance between the selected nano-node and the nano-router increases as l increases; while the proposed scheme will estimate the energy consumption when it selects the nano-node, thus the expected distance between the selected nano-node and the nano-router (which dominates the possible energy consumption) is relatively stable, especially for the case with a large node density, the proposed scheme can always find a suitable nano-node in the near region of the nano-router such that the average path loss can keep constant as l increases.

Regarding the impacts of other key parameters on the performance of path loss, we can see from Figure 4 that the external request arrival rate λ has little impact since it is almost independent of the data collection process. Moreover, the nano-node density μ has almost no influence on the path loss performance of the greedy scheme, however, increasing μ can improve the path loss performance of the proposed scheme remarkably.

6. CONCLUSION

This paper proposed an energy-efficient data collection scheme for a practical Body Area Nanonetwork with the consideration of transmission path loss. Under this network scenario, the energy consumption of data collection is largely determined by the distance between the nano-nodes and nano-routers. Thus, we first intentionally introduced a wake-up region to reduce the set of feasible nano-nodes which could be selected to collect and send the external requested information. We then adopted a novel nano-node selection strategy to select the node with the maximal remaining energy after the data collection process, which further saved the energy consumption and explicitly improved the transmission quality. Finally, simulations were conducted for both the proposed scheme and the benchmark greedy scheme. The results demonstrated the efficiency of the proposed scheme in terms of its average available energy and average path loss.

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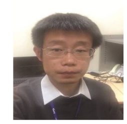

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