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External Biomedical Device Relaying Body Sensor Network scheme

Xidong Zhang*[1,2], Heng Zhang[3], Guixia Kang[1], Ping Zhang[1], and Hui Li[2]
[1]Key Laboratory of Universal Wireless Communication, Ministry of Education, Beijing University of Posts and Telecommunications
10th Xitucheng Road, Beijing, P.R. China
[2]Department of Aero Equipment, Institute of Army Aviation
9th Taihu Road, Beijing, P.R. China
[3]China Equipment System Engineering Corporation
20th Fuxing Road, Beijing, P.R. China
*corresponding author, e-mail: st0rm@126.com

Abstract

Biological parameters acquiring devices are very important in Ubiquitous Medical/Health Care system as they are responsible for gathering physical parameters for further analyze. It is natural that they form a wireless network when they transmit the collected data, and the network is referred to as BSN. Energy efficiency is vital in wireless Body Sensor Network (BSN) because the replacement of power resources of the devices implanted in human body is extremely costly. Considering the difference between In-body channel and special channel, a novel BSN transmission scheme, Coop BSN, is proposed in this paper. In Coop BSN, The transmission of Internal Biomedical Devices is divided into two steps as the external devices are used as relays. The first step is the IBD-EEBD transmission, in which IBDs transmit the data they collected with a modified cooperative algorithm. The second step is EEBD-Coordinator transmission, in which multiuser diversity is exploited. With the division of the transmission, the overall transmission energy efficiency is optimized. Theoretical analyze and experimental results showed that, the scheme can prolong the life time of the sensing devices, especially devices implanted in human body in BSN, and can improve the feasibility of BSN.

Keywords: *Ubiquitous Network, BSN, Relay, Power Saving, Cooperative Transmission, Multiuser Diversity*

1. Introduction

Ubiquitous Medical/Health Care Application is one of the important branches of the Ubiquitous network [1]. The obtaining of biological parameters is the base of the entire Ubiquitous Medical/Health Care system. Basically, the biological parameters are acquired by the devices that are placed near patients or even implanted in their bodies. Naturally, all the devices are considered to be organized in the form of wireless network. Therefore, on the basis of Wireless Sensor Network (WSN), the concept of wireless body sensor network (BSN or WBSN) is proposed, which have recently drawn increasing attention in both academic and industrial areas.

BSN is a network that consist of all the Biomedical Devices (BD) near human body or implanted in human body [2]. Those BDs can acquire the following information: some of the important physical parameters such as temperature, blood glucose, blood pressure and Electrocardiograph (ECG); body activity or motion of the patient; the environmental condition that the patient is in. After some necessary processes, the BDs transmit the information to the nearby Coordinator that is responsible for bringing the information to servers for storage and further process. The designing of BDs and transmission technology turn out to be very important in BSN research.

The BDs can be divided into two categories according to the place they are deployed. The first one is Internal Biomedical Devices (IBD), which includes implantable or swallowable biomedical devices, such as implantable blood glucose monitor and pill-shaped microcameras.

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The second one is External Biomedical Devices (EBD), which includes the biomedical devices that acquire physical/environmental parameters or human motion information from the outside of human body, such as blood pressure transducer, blood oxygen saturation sensor, acceleration transducer and so on.

Those BDs are all placed near/in human body, thereby their wireless transmissions are greatly affected by human body. The conventional wireless channel models cannot be directly used in the analyzing of BSN. In the literature of BSN, there are three different types of communication conditions. First one is Off-body Communication, in which the devices that are placed on the surface of human body communicate with the devices that are some distance away. Spatial channel is mainly concerned in Off-body Communication. Second one is On-body Communication, the communicating peers are both placed on the surface of human body. Signals are transmitted through human skin and superficial layer tissues, known as On-body Channel. Third one is Intra-Body Communication (IBC). In IBC, one communicating part is implanted device, and the other part is either inside or upon human body. Signals are transmitted through human internal tissues, which is called In-body Channel.

There have already been some researches on all the above mentioned channels. [3] proposed a multilayer mathematical model using volume conductor theory for galvanic coupling IBC on a human limb with consideration on the inhomogeneous properties of human tissues. [4] developed a preliminary two dimensional model for IBC. In [5], human tissue is modeled as the combination of resistors and capacitors. [6] discussed a new wireless implantable BSN that operates in medical implant communication service (MICS) frequency band.

As human body have great effect on wireless signals, the channel quality near human body may vary dramatically. Severe channel impairment can be mitigated through the use of diversity. As an important diversity method, cooperative transmission can be exploited in BSN. Among the MIMO cooperative strategies, opportunistic relay selection is an outage-optimal and low-complexity strategy [7]. Recently, one of the opportunistic relay selection method, multiuser diversity (MUD) based relay selection has attracted significant attention. In MUD, diversity is attained through the help of relays. By letting only the user with the highest instantaneous signal-to-noise ratio (SNR) transmit at a given time, MUD gain can be collected in the form of improved outage performance or increased total throughput. [8] developed and analyzed a distributed method to select the best relay that required no topology information and was based on local measurements of the instantaneous channel conditions. The scheme achieved the same diversity-multiplexing tradeoff as achieved by more complex protocols in which coordination and distributed space-time coding for M nodes is required. In [9], the performances of amplify-and-forward (AF) and decode-and-forward (DF) in opportunistic relay are analyzed separately. The opportunistic relay selection in [9] were done in initiative manner or passive manner. [10] proposed an efficient scheme for the combined use of cooperative diversity and multiuser diversity considering DF opportunistic relaying strategy.

There are few researches concerning cooperative communication in BSN for now. [11] exploited cooperative transmission scheme in the communication between IBDs and Coordinator in BSN. The strategy increased the energy efficiency comparing with single node transmission, but the difference between In-body channel and spatial channel was not fully considered. As to the cooperative strategies with opportunistic relay selection, there are even less researches in the field of BSN.

In this paper, we propose a BSN cooperative transmission scheme based on the relay of EBD in BSN (Coop BSN). Aiming at maximize the lifetime of IBDs and minimize the total power consumption, Coop BSN exploited the features of IBDs and EBDs, and separate the transmission on the In-body channel and spatial channel.

The remainder of the paper is organized as follows: Section 2 introduces the network architecture and describes the opportunistic cooperative transmission procedure of Coop BSN. In Section 3, the outrage performance of the system is analyzed . Simulation results and performance comparation are given in section 4. Section 5 concludes the paper.

2. Architecture and Data Transmission of Coop BSN

As long as two different channels, In-body channel and Spatial channel, are both involved in the transmission of BSN, simple network architecture cannot optimize the power efficiency of BDs, especially IBDs. In this paper, in order to maximize the power efficiency of BDs, we propose a novel BSN architecture to separate the transmission on In-body channel and Spatial channel by exploiting the relay of EBDs.

IBDs are implanted in the body of patients, therefore it is pricey to have their power source replaced. Furthermore, the harm caused by IBD wireless transmission must be considered. For these reasons, the transmission power of IBDs must be strictly restricted. As to EBD, the restrictions on their transmission are much less, and their power sources can be easily replaced, so it's proper for them to bear more transmission burdens.

In Coop BSN scheme, the data transmission of IBD is composed of two hops, In-body channel transmission and Spacial channel transmission. In-body channel transmission is operated on the MICS defined frequency band, while Spacial channel transmission is operated on 2.4GHz frequency band. Enhanced External Biomedical Devices (EEBD) is introduced in Coop BSN. Comparing with ordinary EBD, EEBD is equipped with a module that supports the communication on MICS defined frequency band, which enables it to receive the signal transmitted by IBD. EEBDs can then be used to forward the data from IBD to the Coordinator.

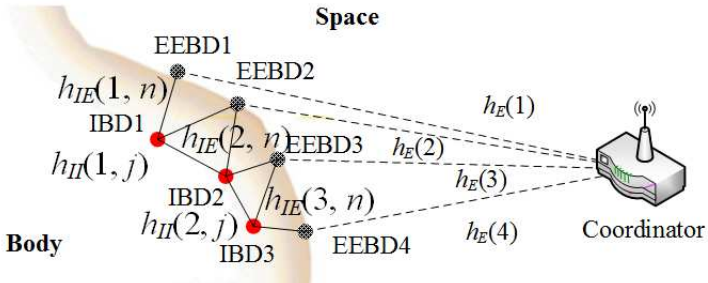

Figure 1. Coop BSN architecture.

Coop BSN architecture is shown in Figure 1. Where $h_{II}(i,j)$ denotes the channels between the ith and jth IBD, $h_{IE}(i,n)$ denotes the channels between the ith IBD and nth EEBD. $h_E(n)$ denotes the channels between the nth EEBD and the Coordinator. There are two steps in the transmission in Coop BSN. The first step is IBD-EEBD transmission which is based on a modified decode and forward (DF) cooperative transmission. The second step is EEBD-Coordinator transmission which is based on MUD.

2.1. IBD-EEBD Cooperative Transmission

IBDs are implanted in human body. Comparing with ordinary WSN nodes, they have much smaller sizes, lower operational capability and less power supply. Therefore, in the design of IBD-EEBD transmission algorithm which is operated on In-body channel, it is required that the energy consumption should be small enough and the algorithm should be simple enough while transmission veracity is guaranteed. In this paper, a modified DF cooperative transmission algorithm is designed.

Normally, there are only a few IBDs in human body, so they are all partners with each other in the cooperative transmission. The time slot allocation scheme of IBD-EEBD DF cooperative transmission is demonstrated in Figure 2. It can be seen from the figure that, in each cycle, every IBD has a great number of time being in sleep mode. In Data Acquisition phase, all IBDs acquire biological parameters with their sensing components and store them temporarily. Later, each IBD is assigned a time slot to transmit the acquired data. So the data transmissions of IBDs are in a Time Division Multiple Address (TDMA) manner, data collision can be avoided hence.

In Data Transmission phase, each IBD is in active mode, and transmit data in the assigned time slot. While the other time in data transmission phase, all nodes receive and store the data

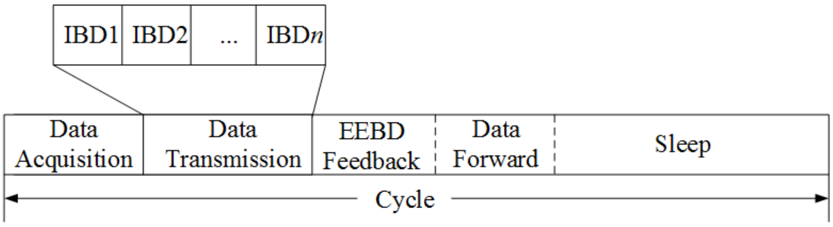

Figure 2. Workflow of IBD-EEBD Cooperative Transmission.

transmitted by other IBDs. As the transmission power of IBDs are limited, an EEBD that is far from an IBD may fail to receive the data transmitted by the IBD. In order to make sure that all EEBDs can receive the data transmitted by each IBD, EEBD Feedback phase and Data Forward phase is settled. In EEBD feedback phase, all IBDs are still in active mode and ready to receive the acknowledgement from EEBDs. All EEBDs contain the sequence numbers they received from IBDs in the feedback signals. The IBDs that receives a feedback signal then compare the sequence numbers with the data from all IBDs stored in itself, to recon that if the EEBD received all the data transmitted by IBDs. If all the EEBDs have received all the IBD data, all IBDs enter sleep mode in advance, otherwise, it comes to Data Forward phase. In Data Forward phase, the IBDs that determined that an EEBD did not receive all IBD data forward the data they stored in Data Transmission phase in an allocated time slot, and sleep in the other time slots.

The above procedure is a modified DF cooperative transmission, which can be referred to as Delayed Decode-and-Forward (DDF) cooperative transmission. With the operation in the first step, it is guaranteed that all EEBDs receive all the IBD data.

2.2. EEBD-Coordinator MUD Transmission

MUD is proved to be able to improve the transmission performance when there are more than one users, and is easy to implement. In BSN, all EEBDs are considered as users, and Coordinator is considered as base station. All EEBDs transmit reference signals to Coordinator periodically, and Coordinator evaluate the channel conditions between itself and all the EEBDs according to the reference signals. The Coordinator broadcast the data transmission permission periodically, which appoints the EEBD that has the best channel condition can proceed with data transmitting. When EEBDs need to transmit data to the Coordinator, they receive the data transmission permission. Then the appointed EEBD combines the data it acquired with the IBD data and transmit it to the Coordinator. The workflow of EEBD-Coordinator MUD transmission is shown in Figure 3. After this procedure, the second step is finished.

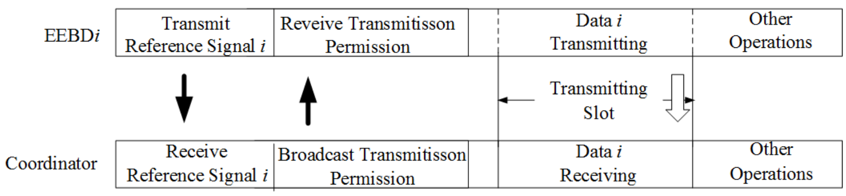

Figure 3. Workflow of EEBD-Coordinator MUD transmission.

3. Outage Probability Analysis

3.1. Outage Probability in IBD-EEBD DDF Cooperative Transmission

In IBD-EEBD DDF cooperative transmission, the In-body channel path loss model is [5]:

$$T\left(d,f\right)=\frac{P_{RX}}{P_{TX}}=\frac{\left(Kf\right)^{2}\left(1+f/2f_{0}\ \right)^{2}}{\left(1+f/2f_{0}\ \right)^{P}}A_{G} \tag{1}$$

Where $K=3\times10^{-9}$, $f_0=10^7/D$, $P=\left\{\begin{array}{c}3, D>0.8\\4, else\end{array}\right.$, D is In-body channel length, AG is the size of reference ground of human surface. Commonly, its value is $A_G=0.0025m^2$. f is the signal frequency. Substituting the MICS defined frequency f=402MHz into (1) and trimming it, we have

$$T'\left(d\right)=\frac{P_{TX}}{P_{RX}}=\left\{\begin{array}{c}277.78\left(1+20.1d\right)d>0.8\\277.78\left(1+20.1d\right)^{2}else\end{array}\right. \tag{2}$$

Conversing its unit, we have the path loss model of In-body channel:

$$P_{IL}\left(d\right)=10\lg\left(T'\left(d\right)\right) \tag{3}$$

It is evident that the path loss is mainly decided by the distance between transmitter and receiver. Assume that there are M IBDs and N EEBDs in BSN. Assume the transmitting power of IBD is P_I, the Additive White Gaussian Noise (AWGN) on the In-body channel is N_{I0} (both in dBm). When an IBD broadcasts its data, the Signal Noise Ratio (SNR) of the received signal of another IBD is:

$$\gamma_{ii}=P_I-P_{IL}\left(d_{ii}\right)-N_{I0} \tag{4}$$

Assume the SNR threshold of received signal of IBD is η_I, then the distance threshold between an IBD and its partner is:

$$d_{thII}=1.79\times10^{-4}e^{\frac{1}{10}\left(P_I-\eta_I-N_{I0}\right)} \tag{5}$$

Let $D\left(I\right)$ denotes the collection of decodable partner IBDs. As to IBDm, the probability that its collection of decodable partner IBDs exists is:

$$\Pr\left\{D_m\left(I\right)\right\}=\Pr\left\{d_{Imn}<d_{thII}\right\} \tag{6}$$

Where d_{Imn} is the distance between IBDm and all the other IBDs.

In MICS, it is defined that the maximum transmitting power is P_{Imax}=25mW. In our algorithm, we define a maximum IBD transmitting power P'_{Imax}=15mW (or 11.7dBm). It can be calculated that, when the sensitivity of IBD receiver is under -74dBm, d_{thII}=0.94m. Generally speaking, most IBDs are implanted in the upper part of the body, therefore the distances between IBDs usually fall in the distance threshold. Under such circumstance, we have $D_m\left(I\right)=\left\{I_n, n=1,2,\ldots,M-1\right\}$ and $\Pr\left\{D_m\left(I\right)\right\}=1$.

Similarly, when the partner IBDs forward the data from an IBD to EEBDs, the SNR of the received signal of EEBD is:

$$\gamma_{ie}=P_I-P_{IL}\left(d_{ie}\right)-N_{I0} \tag{7}$$

Assume the SNR threshold of received signal of EEBD is η_E, then the distance threshold between an IBD and terminal EEBD is:

$$d_{thIE}=1.79\times10^{-4}e^{\frac{1}{10}\left(P_I-\eta_E-N_{I0}\right)} \tag{8}$$

Let $D(E)$ denotes the collection of decodable EEBDs. As to IBDp, the probability that its collection of decodable terminal EEBDs exists is:

$$\Pr\left\{D_p\left(E\right)\right\}=\Pr\left\{d_{Ipq}<d_{thIE}\right\} \tag{9}$$

Where d_{Ipq} is the distance between IBDp and EEBDq.

When P'_{Imax}=15mW, it can also be calculated that, when the sensitivity of EEBD receiver is under -79dBm, dthIE=1.55m. Then the minimum distance between IBDs and EEBDs usually fall in the distance threshold. Under such circumstance, we have $D_p(E) = \{E_p, p = 1, 2, \ldots, N\}$ and $\Pr\{D_p(E)\} = 1$.

The outage probability in the two hop cooperative transmission is:

$$P_{OUT} = 1 - \Pr(D_m(I)\, D_p(E)) \tag{10}$$

Therefore, if the performances of IBDs and EEBDs all meet the requirement mentioned above, we can have $P_{OUT} = 0$.

3.2. Outage Probability in EEBD-Coordinator MUD Transmission

Assume that the channels between N EEBDs and the Coordinator, $h_E(j)\ (j = 1, 2, \ldots N)$, are Rayleigh fading channels and are independent, then the bandwidth capacity is:

$$I_{MU} = \max_{i=1}^{N} \log_2\left(1 + \gamma |h_E(i)|^2\right) \tag{11}$$

Where γ is the average SNR between all the EEBDs and the Coordinator. Assume that the SNR threshold of received signal of the Coordinator is η, then the outage probability of MUD transmission is:

$$\begin{aligned} P_{OUT} &= \Pr(I_{MU} < \eta) \\ &= \prod_{i=1}^{N} \Pr\left[\log_2\left(1 + \gamma |h_E(i)|^2\right) < \eta\right] \\ &= \prod_{i=1}^{N} \left(1 - e^{\frac{2^\eta - 1}{\gamma}}\right) \end{aligned} \tag{12}$$

According to the properties of exponent distribution, when the average SNR is high enough, (12) can be rewritten as:

$$P_{OUT} = \left(\frac{2^\eta - 1}{\gamma}\right)^N \tag{13}$$

It can be seen from (13) that, the outage probability of MUD transmission varies inversely with γ's N-th power. On the perspective of diversity, EEBD-Coordinator MUD transmission has the same diversity degree with more complex Space-Time Code (STC) cooperative transmission.

4. Simulation Results

Consider a BSN shown in Figure 1. Assume that BPSK (Binary Phase Shift Keying) is adopted in all BDs' transceivers, and the transmission rate is R_b=10kbps. Assume that the AWGN on the special channel has mean of 0dB and variance of 5.6dB, and the transmitting power of IBD is P'_{Imax}=15mW. Assume that the capacity of the BD energy resource is 100mAh, and the power consumption of BDs in the sleep mode is approximately 0mA.

The compare of energy consumption of Coop BSN and other schemes is shown in Figure 5. In DT (direct transmission) scheme, an IBD directly transmits data to the Coordinator, while in Amplify-and-forward (AF) cooperative transmission scheme, the partner IBDs AF the data from an IBD. Cooperative transmission under BSN (BSN CT) is the scheme proposed in [11] which considered the impact of In-body channel. It can be seen from Figure 4 that, if cooperative transmission is used, the energy efficiency of transmission is improved greatly when the transmission distance is not very short. BSN CT has better performance than AF as it jointly optimized modulation index and partner number having In-body channel considered, but as the transmitting technology remains the same while In-body channel and special channel are different, the energy efficiency of this scheme is not appealing. Coop BSN scheme made use of the feature of both IBD and EEBD. EEBDs forward the data from IBD, thereby the transmission on In-body channel and special channel is separated, and the overall transmission energy efficiency is improved.

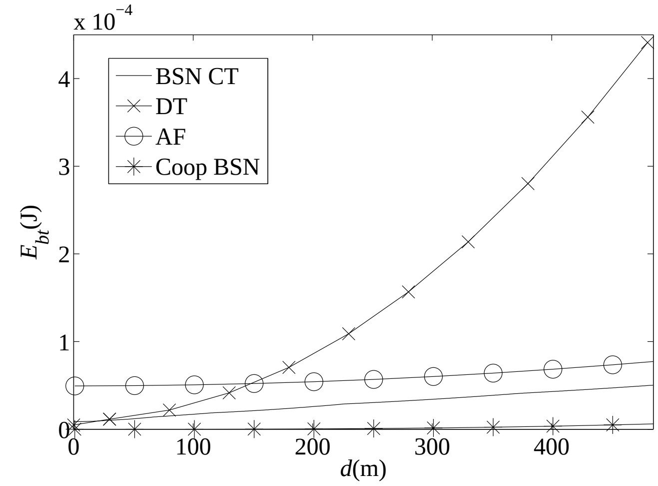

Figure 4. Energy consumption comparison between Coop BSN and other schemes.

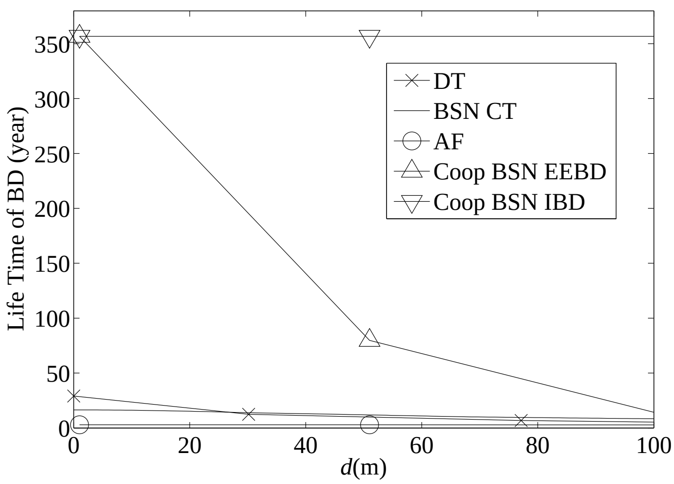

Figure 5. BD life time comparison between Coop BSN and other schemes.

The life time of BDs in Coop BSN and other schemes are compared in Figure 5. The concept of life time is that when all the power is used to transmit data, the time duration before the power supply in a BD is depleted. Assume that a BD transmits data for 800 seconds in one day. It can be seen from Figure 5 that, when the transmission distance is relatively short, BDs in DT scheme have longer life time, but with the increase of the transmission distance, cooperative is proved to prolong the life time of BDs. BSN CT has longer life time than AF, but as all BDs transmit on the 2.4GHz frequency band, the signals fad greatly in human body, the energy efficiency of this scheme is not high enough. In Coop BSN scheme, IBDs only have to transmit the data they collected to EEBDs cooperatively on the In-body channel, so the power consumption do not vary with the distance of the Coordinator. Furthermore, when EEBDs transmit data to the Coordinator on the special channel, they can have MUD gain, hence a higher transmission energy efficiency is gained. From the perspective of BSN implement, the higher energy efficiency of BDs in Coop BSN, especially IBDs, can make the duration of IBDs much longer, thereby improve the feasibility of BSN.

5. Conclusion

In this paper, a BSN cooperative transmission scheme based on the relay of EBD is proposed. In the proposed shceme, the transmission of IBDs is divided into two steps. The first step is the IBD-EEBD transmission, in which IBDs transmit the data they collected with DDF cooperative algorithm. The second step is EEBD-Coordinator transmission, in which MUD is exploited. With the division of the transmission, the overall transmission energy efficiency is optimized. Theoretical analyze and experimental results showed that, the scheme can prolong the life time of BDs, especially IBDs in BSN. This feature can help to improve the feasibility of BSN.

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