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A Cooperative Transmission Strategy for Body-Area Networks in Healthcare Systems

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ABSTRACT Wireless body area networks (BANs) have attracted enormous attention due to the promising applications in healthcare systems. Energy saving is one of the major challenges in wireless BANs, because the sensors operating on or inside a human body are energy limited. As the applying cooperative communications offers energy saving, it is necessary to utilize the sensor devices jointly in BANs to form cooperative communication. In this paper, the energy consumption models of cooperative transmission strategies are built over in- and on-body wireless communication links for direct and relay transmission scenarios. In relay cooperative strategy, the implantable and wearable devices work together by using a cooperative multiple input multiple output (MIMO) technique. In direct cooperative strategy, two wearable devices operate as the cooperative MIMO. In these ways, the energy savings of both direct and relay transmissions are achieved during the data transmission in BANs. Moreover, the closed-form expression of end-to-end average bit error ratio (BER) is derived toward minimizing the required transmission power for relay transmission scenario. In the results, it is demonstrated that the significant energy savings of the proposed cooperative transmission strategies can be obtained compared with the existing approaches under the same conditions.

INDEX TERMS Body area networks (BANs), cooperative, energy saving, multiple input multiple output (MIMO).

I. INTRODUCTION

Wireless body area networks (BANs) [1], [2] comprise of low power sensor devices inside or on the human body and are used to collect and transmit the physiological signals, e.g., electroencephalography (EEG), electrocardiography (ECG), or temperature, for healthcare applications [3]. According to the location of the sensors, BANs can be split into in-body and on-body area networks, respectively. In-body area networks provide communication among implanted sensors, whereas on-body area networks provide communication among wearable sensors [4]–[6]. One critical research task for both in- and on-body area networks is energy saving because the sensors are usually powered by the energy-limited batteries. Charging and replacement of sensors are not preferable and even not a viable choice in some cases, especially in in-body area networks. Therefore, the concept of cooperative communications [7]–[15] has been applied to wireless BANs to address the challenge of energy saving. In [16], an energy consumption model based on cooperative multiple input multiple output (CMIMO) is proposed for BANs. It shows that the total energy consumption is reduced within a threshold compared with the single input single output (SISO) strategy when the cooperative node number and modulation constellation size are selected. Ntouni *et al.* [17] designed an energy efficient communication scheme for wireless biomedical implant systems. In the design, the implantable devices transmit the measured data to an off-body access point via wearable devices which act as the cooperative relays. In this way, the reliable and energy efficient communications are achieved. A system level energy consumption model associated with transmission distance and transmission data rate for on-body wireless communications is presented in [18], in which the total energy consumption is saved by optimizing the transmission data rate. In [19], a game theoretic approach is proposed to investigate the problem of relay selection and power control in wireless BANs. Misra *et al.* [20] proposed a cooperative approach based on the Nash bargaining solution (NBS) for data rate tuning among sensors in wireless BANs to meet the quality of service (QoS).

All the aforementioned literatures consider the cooperative transmission to design energy efficient wireless BANs but there is no literature investigating the index modulation technique [21] in the design of wireless BANs. In fact, index modulation provides important advantages which are quite useful in wireless BANs. For example, it can effectively avoid inter channel interference (ICI) and does not require synchronization during the transmission. Moreover, it can achieve more energy efficiency compared to the traditional way due to the diversity gain. Toward these goals, the cooperative transmission strategies with the consideration of index modulation under direct and relay transmissions for wireless BANs are proposed in this paper.

First, the proposed cooperative strategies and energy models are introduced. In the cooperation stage, spatial modulation (SM) [22] as the typical index modulation technique is used to solve the ICI and synchronization problems and improve the energy efficiency. The energy consumption comparisons are then conducted between the proposed strategies and existing strategies in both direct and relay transmission scenarios in order to investigate the energy consumption performance. Moreover, the closed form expression of end-to-end bit error ratio (BER) is derived for fast and convenient evaluation of the performance in the relay transmission scenario since the real experiments are not always available, especially for the power measurements in inside-body environments. Therefore, the theoretical analysis and expression are necessary. The contributions of the paper are two-fold and are as follows.

- New energy models in cooperative transmission strategy are proposed in wireless BANs for energy saving.
- The theoretical end-to-end BER expression is derived mathematically for convenient and fast evaluation in the relay transmission scenario.

The rest of the paper is organized as follows. Section II illustrates the energy models and gives the description of the cooperative strategies. In Section III, the energy consumption comparisons between the proposed strategies and existing strategies are given. The theoretical end-to-end BER expression is derived in Section IV. Finally, the conclusion is given in Section V.

II. SYSTEM MODEL AND ENERGY ANALYSIS

A wireless BAN system model consisting of an implantable device I, two wearable devices (W_0 and W_1), and a receiver R is considered and illustrated in Fig. 1. According to the location of sensor device, it is categorized into implantable sensor, wearable/on-body sensor, and receiver/off-body device. Based on the IEEE 802.15.6 standard [23], the communications among these devices are classified as intra body and on-off body communications. The communication and transmitting power in wireless BANs must comply with the rules adopted by the Federal Communications Commission (FCC) with respect to the frequency band and power limitation, respectively. The bands used in wireless BANs are the Medical Implant Communication Service (MICS) band (402-405 MHz) and the Industrial Scientific and Medical (ISM) band (2.4-2.5 GHz). The maximum transmitting power recommended by MICS and ISM are 25 μW and 0.5 mW, respectively. In Fig. 1, two transmission scenarios A and B are considered. A is relay transmission scenario where implantable device I transmits measured information to receiver R through wearable device W_0 and wearable device W_1 which work as the relay. B is direct transmission scenario where wearable devices directly transmit the measured information to the receiver via cooperative approach.

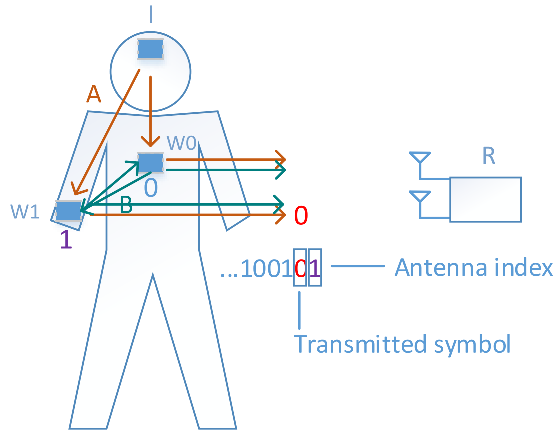

FIGURE 1. System model of cooperative wireless BAN. (A) Implantable device to receiver communication. (B) Wearable device to receiver communication.

A. ENERGY CONSUMPTION OF RELAY TRANSMISSION A

In relay transmission scenario, because of the power limitation of the implantable device, the transmission distance of it is short. As a result, the measured information from implantable device is transmitted to the wearable devices as the first step and then wearable devices forward the obtained information to the receiver. The data flow between implantable device and wearable devices is defined as intra body transmission, whereas the data flow between wearable devices and off-body receiver is defined as on-off transmission. For the intra body transmission, the implantable device broadcasts the information to the relay wearable devices via the path loss channel. After receiving the information transmitted by implantable device, the wearable devices W_0 and W_1 transmit the received information via the SM approach, as it is explained in Fig. 1 (A). For each time instant, the information sequence received by the W_0 and W_1 is composed of the multiple quadrature amplitude modulation (MQAM)/multiple phase shit keying (MPSK) modulated symbol part and antenna index represented part (0 or 1). 0 and 1 represent W_0 and W_1, respectively. Only the MQAM/MPSK modulated part is transmitted, and the other part is reserved for the selection of the index of the active transmit antenna that performs the transmission of the MQAM/MPSK modulated bits. Finally, the bits represented by antenna index will be detected at the receiver. In this way,

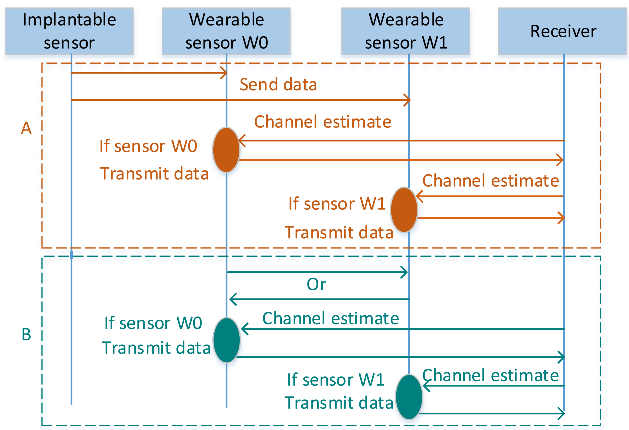

FIGURE 2. The communication process of cooperative wireless BAN. (A) Implantable to receiver communication. (B) Wearable device to receiver communication.

compared with the traditional signal constellation diagram, the antenna plays a role of the second constellation diagram. The whole communication process can be explained by using Fig. 2 (A). For an example, as shown in Fig. 1 (A), if 01 is the obtained bit sequence transmitted from implantable device I, antenna 1 (wearable device W_1) will be active for transmitting the bit 0 which is modulated by MPSK. At receiver R, in addition to the demodulated bit 0, the bit 1 represented by the antenna index will be detected as well.

Based on the above description, the total energy consumption per bit in wireless BAN can be formulated as

$$E_{\mathrm{bt}} = E_{in} + E_{on} \tag{1}$$

where E_{in} and E_{on} are energy consumptions in intra phase and on-off phase, respectively.

For the intra body phase, unlike the traditional wireless communication system, the path loss in channel between implantable device and wearable devices is complex and can be express as

$$P_L^r = P_L^r(d_0) + 10n\log_{10}\frac{d}{d_0} + s \tag{2}$$

where $P_L^r(d_0)$ is the path loss at a reference distance d_0 with the value of 50 mm; n is the path loss exponent; d is the transmission distance; and s is a random variable that is normally distributed. As the result, the transmission power in the intra body area for relay transmission is given by

$$P_{in}^r = \bar{E}_{b,in} \times \frac{P_L^r}{G_t G_r} M_l N_f R_b \tag{3}$$

where $\bar{E}_{b,in}$ is the required energy per bit at the receiver for a given BER requirement; G_t and G_r are the transmitter and receiver antenna gains, respectively; M_l is the link margin compensating the hardware process variations; R_b is the bit rate; and N_f is the receiver noise. It should be noted that N_f is given by $N_f = N_r/N_0$ where N_r is the power spectral density (PSD) of the total effective noise at the receiver input and N_0 is the single-sided thermal noise PSD at a room temperature with a value $N_0 = -171$ dBm/Hz [24]. In (3), when binary phase shift keying (BPSK) is used, $\bar{E}_{b,in}$ can be calculated using the relationship between signal to noise ratio (SNR) and BER as show [25]

$$P_{b,in} = \mathrm{Q}\left(\sqrt{2\bar{E}_{b,in}/N_0}\right) \tag{4}$$

where Q (x) is the Q-function. By considering the circuit power $P_{c,in}^r$, the total energy consumption per bit in the intra body phase for relay transmission is given as

$$E_{in}^r = (1+\alpha)\bar{E}_{b,in} \times \frac{P_L^r}{G_t G_r} M_l N_f + \frac{P_{c,in}^r}{R_b} \tag{5}$$

where $\alpha = \xi/\eta - 1$ with ξ is the peak-to-average ratio (PAR) and η is the drain efficiency of the radio frequency (RF) power amplifiers [21].

For the on-off body phase, the normal communication link is adopted for calculating the energy consumption. Following the foregoing analysis, the energy consumption per bit of the on-off body phase is given by

$$E_{on} = (1+\alpha)\bar{E}_{b,on} \times \frac{(4\pi d)^2}{G_t G_r \lambda^2} M_l N_f + \frac{P_{c,on}}{R_b} \tag{6}$$

where $\bar{E}_{b,on}$ is the required energy per bit at the receiver for a given BER requirement in the on-off body phase; λ is the carrier wavelength; and $P_{c,on}$ is the circuit power in on-off phase for relay transmission. Because in on-off body phase W_0 and W_1 operate in SM approach and it is easy to get $\bar{E}_{b,on}$ by using BER and SNR plotting. For a given BER, the $\bar{E}_{b,on}$ is calculated using SNR value and PSD of the thermal noise N_0. The total circuit power of the both intra area phase and on-off area phase with N_t transmit and N_r receive antennas are given by

$$P_{c,on} = P_{c,in}^r \approx N_t(P_{DAC} + P_{mix} + P_{filt}) + 2P_{syn} + N_r(P_{LNA} + P_{mix} + P_{IFA} + P_{filr} + P_{ADC}) \tag{7}$$

where P_{DAC}, P_{mix}, P_{LNA}, P_{IFA}, P_{filt}, P_{filr}, P_{ADC}, and P_{syn}, are the power consumption values for the DAC, the mixer, the low noise amplifier (LNA), the intermediate frequency amplifier (IFA), the active filters at the transmitter side, the active filters at receiver side, the ADC, and the frequency synthesizer, respectively. The values of P_{DAC}, P_{ADC}, and P_{IFA} can be calculated using the model introduced in [27]–[30]. For the intra body transmission, $N_t = 1$ and $N_r = 2$ are used since the broadcasting is executed in this phase. In the on-off body transmission, $N_t = 1$ and $N_r = 2$ are used because SM is carried out and for each time instant, only one antenna works.

Considering the energy consumption described earlier, the total energy consumption of the proposed cooperative strategy for the relay transmission can be expressed as

$$E_{\mathrm{bt}}^r = (1+\alpha)[\bar{E}_{b,on}(\frac{4\pi d}{\lambda})^2 + \bar{E}_{b,in}P_L^r]\frac{M_l N_f}{G_t G_r} + \frac{P_{c,on}}{R_b} + \frac{P_{c,in}^r}{R_b}. \tag{8}$$

B. ENERGY CONSUMPTION OF DIRECT TRANSMISSION B

In direct transmission scenario, the wearable device collects the measured information and directly transmits to the receiver through CMIMO approach. As shown in Fig. 1(B), wearable device W_0 or W_1 directly transmitting information to receiver R is considered. At first, the wearable device which collects information transmits the collected information to the other wearable device, so that both wearable devices have the same information. After that, the SM approach is executed between the wearable devices and the receiver, as it is explained in the Fig. 2 (B).

The total energy consumption analysis of the direct scenario is similar to that of relay scenario. Instead of broadcasting information by implantable device, the information is transmitted to one wearable device from the other wearable device as the intra body transmission. In the on-off phase, the same cooperative approach used in relay transmission is executed.

For the intra body phase, the path loss channel between two wearable devices is expressed as

$$P_L^d = a\log_{10} d + b + s \tag{9}$$

where a, b are coefficients of linear fitting, respectively. The transmission power in the intra body phase for direct transmission is given by

$$P_{in}^d = \bar{E}_{b,in} \times \frac{P_L^d}{G_t G_r} M_l N_f R_b. \tag{10}$$

As a result, the total energy consumption per bit in the intra body phase for the direct transmission is given by

$$E_{in}^d = (1+\alpha)\bar{E}_{b,in} \times \frac{P_L^d}{G_t G_r} M_l N_f + \frac{P_{c,in}^d}{R_b} \tag{11}$$

where $P_{c,in}^d$ is the circuit power in the intra body phase for direct transmission. For the on-off body phase, the same transmission as the one in cooperative transmission is carried out.

The expression of the total energy consumption is given by

$$E_{\mathrm{bt}}^d = (1+\alpha)[\bar{E}_{b,on}(\frac{4\pi d}{\lambda})^2 + \bar{E}_{b,in} P_L^d]\frac{M_l N_f}{G_t G_r} + \frac{P_{c,on}}{R_b} + \frac{P_{c,in}^d}{R_b}. \tag{12}$$

For the existing cooperative transmission in wireless BANs, the energy consumption in the intra body phase is same as that in the proposed strategies, whereas in the on-off body phase, instead of using cooperative SM transmission, the traditional Alamouti transmission is executed. The expressions of total energy consumption per bit of the existing strategies in the relay and direct transmission scenarios can be derived as (13) and (14), respectively, and which are shown as

$$E_e^r = (1+\alpha)[\bar{E}_{e,on}(\frac{4\pi d}{\lambda})^2 + \bar{E}_{e,in} P_L^r]\frac{M_l N_f}{G_t G_r} + \frac{P_{e,on}}{R_b} + \frac{P_{e,in}^r}{R_b} \tag{13}$$

$$E_e^d = (1+\alpha)[\bar{E}_{e,on}(\frac{4\pi d}{\lambda})^2 + \bar{E}_{e,in} P_L^d]\frac{M_l N_f}{G_t G_r} + \frac{P_{e,on}}{R_b} + \frac{P_{e,in}^d}{R_b} \tag{14}$$

where $\bar{E}_{e,in}$ and $\bar{E}_{e,on}$ are the required energy per bit at the receiver for a given BER requirement in the intra and on-off body phases, respectively; $P_{e,on}$ is the circuit power in on-off body phase for both direct and relay transmissions; $P_{e,in}^r$ and $P_{e,in}^d$ are the circuit power in the intra body phase for relay and direct phases, respectively. The circuit power can be calculated according to (7) by changing the N_t and N_r.

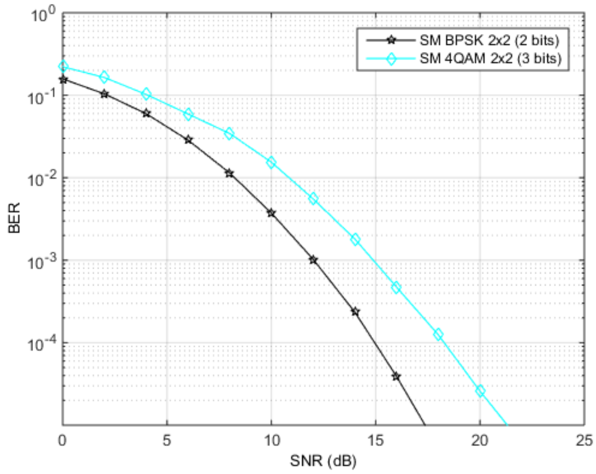

FIGURE 3. The received SNR versus BER for on-off body transmission in the proposed strategy.

III. SIMULATIONS AND ENERGY COMPARISONS

In order to evaluate the energy consumption performance of the proposed strategies, the energy comparisons between the proposed strategies and the existing strategies are given in this section. In the simulation, the following values which are equivalent to those in [16] and [28]–[32] are ued: $B = 10$ kHz, $f_c = 2.5$ GHz, $P_{mix} = 30.3$ mW, $P_{filt} = 2.5$ mW, $P_{filr} = 2.5$ mW, $P_{LNA} = 20$ mW, $P_{synth} = 50$ mW, $M_l = 40$ dB, $N_f = 10$ dB, $G_t G_r = 5$ dBi, $\eta = 0.35$, $N_i = 20$ kb, $P_b = 10^{-5}$, $a = 15.5$, and $b = 5.38$. For the on-off body phase, the results of BER versus SNR used for calculating the required energy consumption per bit at the receiver of the proposed strategies under 2 bits/s/Hz and 3 bits/s/Hz are plotted in Fig. 3; and those results of existing strategies under 2 bits/s/Hz and 3 bits/s/Hz are plotted in Fig. 4. Specifically, Monte Carlo simulations are carried out to find the desired BER and $\bar{E}_{b,on}$ can be calculated based on the SNR value for the given BER. For the intra body phase, the required energy consumption per bit at the receiver of both relay and direct transmission scenarios is obtained via (4).

In the energy consumption comparisons, it is assumed that the average transmission distance in the intra body area is about 0.5 meters. In the proposed cooperative transmission strategies, the transmission is operated with antenna index technique therefore less data will be transmitted when

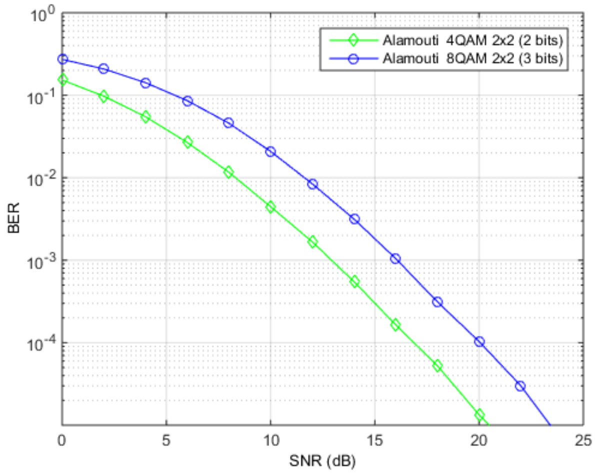

FIGURE 4. The received SNR versus BER for on-off body transmission in the existing strategy.

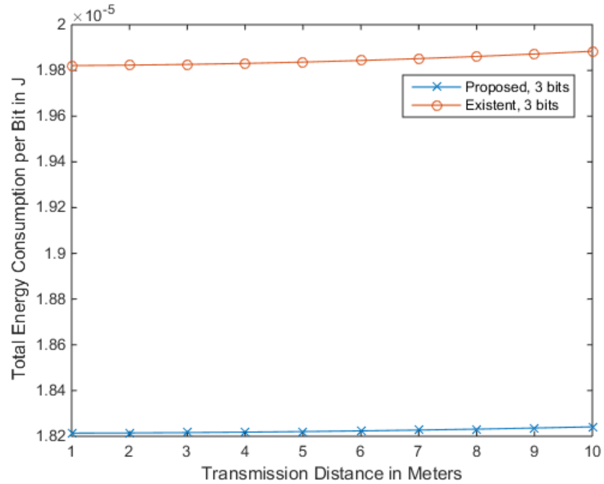

FIGURE 6. Energy consumption per bit over transmission distance under two transmission strategies in relay transmission for 3 bits/s/Hz case.

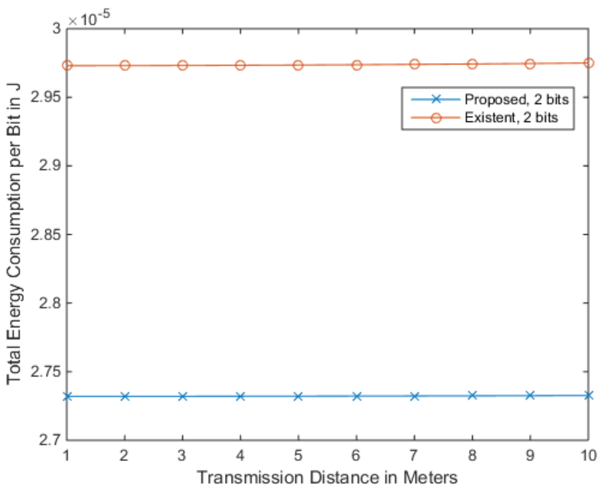

FIGURE 5. Energy consumption per bit over transmission distance under two transmission strategies in relay transmission for 2 bits/s/Hz case.

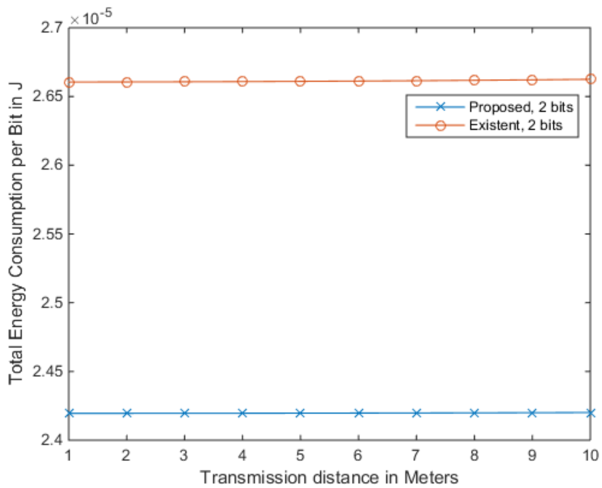

FIGURE 7. Energy consumption per bit over transmission distance under two transmission strategies in direct transmission for 2 bits/s/Hz case.

compared with the existing strategies. Also, because SM technique adopted by the proposed strategies works under single RF chain therefore less circuit energy will be consumed by the proposed strategies compared to existing strategies. Consequently, the proposed cooperative transmission strategies will spend less energy in both transmission part and circuit part. Fig. 5-6 show the energy consumption per bit against transmission distance under the proposed strategy and the existing strategy in relay transmission scenario for 2 bits/s/Hz and 3 bits/s/Hz, respectively. Fig. 7-8 show the energy consumption per bit versus transmission distance under the proposed strategy and the existing strategy in direct transmission scenario for 2 bits/s/Hz and 3 bits/s/Hz, respectively. As shown in all the plots, the proposed strategies outperform existing strategies in terms of energy consumption per bit in different situations due to the efficient transmission schemes. Moreover, the energy consumption per bit of the both strategies in the plots increase as the transmission distance increases due to the fact that longer transmission requires bigger energy. Note that, in both relay and direct transmission scenarios, the energy consumption per bit of the proposed strategies and existing strategies decrease as the transmission rates increase from 2 bits/s/Hz to 3 bits/s/Hz. This can be explained by the reason that in the short transmission distance, the circuit power dominates the total power and circuit power working in short time will bring lower energy.

IV. THEORETICAL BER ANALYSIS FOR RELAY TRANSMISSION

Because the relay transmission environment is more complex compared with the direct transmission environment, finding the theoretical BER expression of the transmission between the implantable device and receiver, namely end-to-end BER, is necessary to evaluate the transmission performance. Due to this reason, in this section, the analytical closed form expression of the end-to-end BER for the relay transmission

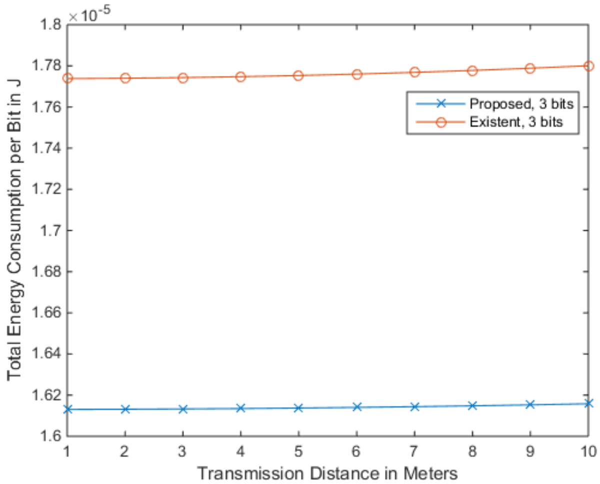

FIGURE 8. Energy consumption per bit over transmission distance under two transmission strategies in direct transmission for 3 bits/s/Hz case.

scenario is derived mathematically. In the intra body phase, considering BPSK modulation, the BER can be expressed by using (4). In the on-off phase, using [33], the BER $P_{b,on}$, is given by

$$P_{b,on} \leq \sum_{q=1}^{M}\sum_{\hat{q}=1}^{M} \frac{N_t N(q,\hat{q})\mu_\alpha^{N_r}\sum_{k=0}^{N_r-1}\binom{N_r-1+k}{k}[1-\mu_\alpha]^k}{M} \quad (15)$$

where $M = 2^b$ with b is modulation constellation size; N_t and N_r are transmit and receive antennas, respectively; $N(q,\hat{q})$ is the number of bits in error; q and $\hat{q}$ are symbol index and estimated symbol index; and k is the distribution of the random variable; $\mu_\alpha = \frac{1}{2}\left(1-\sqrt{\frac{\sigma_\alpha^2}{1+\sigma_\alpha^2}}\right)$ with variance of σ_α^2. The upper band of (15) is given by

$$P_{b,on} = \sum_{q=1}^{M}\sum_{\hat{q}=1}^{M} \frac{N_t N(q,\hat{q})\mu_\alpha^{N_r}\sum_{k=0}^{N_r-1}\binom{N_r-1+k}{k}[1-\mu_\alpha]^k}{M}. \quad (16)$$

When the wearable devices decode and forward the received signal from implantable device to the receiver, the end-to-end BER is given by

$$\begin{aligned} P_{b,end} &= 1-(1-P_{b,in})\times(1-P_{b,on})-P_{b,in}P_{b,on} \\ &= P_{b,in}+P_{b,on}-2P_{b,in}P_{b,on} \end{aligned} \quad (17)$$

Substituting (4) and (16) into (17), (17) can be rewritten as

$$\begin{aligned} P_{b,end} &= Q\left(\sqrt{\frac{2\bar{E}_{b,l}}{N_0}}\right)+\sum_{q=1}^{M}\sum_{\hat{q}=1}^{M} \frac{N_t N(q,\hat{q})\mu_\alpha^{N_r}\sum_{k=0}^{N_r-1}\binom{N_r-1+k}{k}[1-\mu_\alpha]^k}{M} \\ &\quad -2Q\left(\sqrt{\frac{2\bar{E}_{b,l}}{N_0}}\right)\sum_{q=1}^{M}\sum_{\hat{q}=1}^{M} \frac{N_t N(q,\hat{q})\mu_\alpha^{N_r}\sum_{k=0}^{N_r-1}\binom{N_r-1+k}{k}[1-\mu_\alpha]^k}{M} \end{aligned} \quad (18)$$

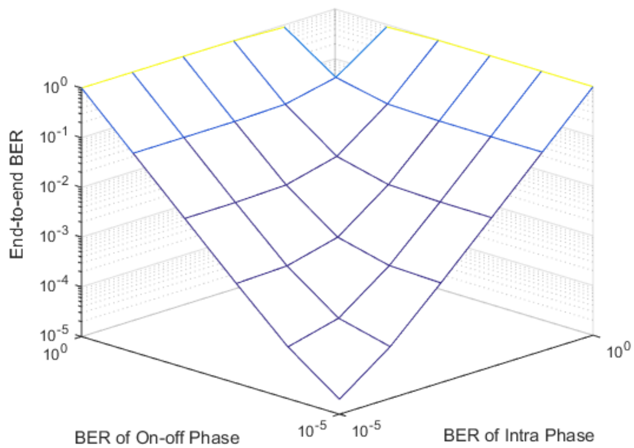

FIGURE 9. BER relationship among intra phase, on-off phase, and end-to-end phase.

The closed form expression of the end-to-end BER is constructed in (18) and the corresponding relationship is plotted in Fig. 9. It shows that for each given intra and on-off BER, a corresponding end-to-end BER can be found. The applications of this end-to-end BER construction are two-fold. First, this expression can help minimize the required transmission power for meeting a given QoS requirement in terms of BER. Second, this expression can also maximize the BER performance under the allowable transmission power of the implant and wearable devices. For the first application, the problem can be formulated as

$$\begin{aligned} &\min_n \; P_{in}^r \leq P_{req,1} \text{ and } P_{on}^r \leq P_{req,2} \\ &s.t \; P_{b,end} \leq P_{b,req}. \end{aligned} \quad (19)$$

where $P_{req,1}$ and $P_{req,2}$ are the given maximum transmission power of implantable and wearable devices for the safety of human body, respectively; P_{on}^r is the transmission power of the on-off phase; and $P_{b,req}$ is the maximum BER value as the constraint. The problem of the second application can be formulated as

$$\min_{n} P_{b,end}$$
$$s.t\ P_{in}^{r} \leq P_{req,1} \text{ and } P_{on}^{r} \leq P_{req,2}. \quad (20)$$

V. CONCLUSION

In this paper, energy consumption models of cooperative transmission strategies were proposed under direct and relay transmission cases for wireless BANs. For the direct transmission, the cooperative transmission is carried out whereas for the relay transmission, because of the limited transmission power of the implantable device, it is necessary to utilize the wearable devices as the relay points to forward the information to the receiver. The energy saving performance of the proposed cooperative strategies were demonstrated by comparing with the existing strategies in the direct and relay communication environments of the wireless BANs where the implantable device, wearable devices, and receiver are involved. The comparisons were conducted under the transmission distance suggested by IEEE 802.15.6 with consideration on the transmission energy and circuit energy. Later, because of the complex communication environment of the relay transmission, the BER relationship of the end-to-end expression in the relay transmission scenario is derived mathematically for convenient evaluation of the communication performance in wireless BANs. Moreover, the optimization examples of utilizing the end-to-end BER relationship for reducing the transmission power and designing energy efficient wireless BAN systems are provided.

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