Energy Efficient Cooperative Communications for Wireless Body Area Networks

by

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I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

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Abstract

It is expected that Wireless Body Area Network (WBAN) will greatly improve the quality of our life because of its myriad applications for our human beings. However, one of the challenges is to design energy efficient communication protocols to support the reliable communication as well as to prolong the network lifetime. Cooperative communications have the advantage of spatial diversity to combat multipath fading, thus improving the link reliability and boosting energy efficiency.

In this thesis, we investigate the energy efficient cooperative communications for WBAN. We first analyze the outage performance of three transmission schemes, namely direct transmission, single relay cooperation, and multi-relay cooperation. To minimize the energy consumption, we then study the problem of optimal power allocation with the constraint of targeted outage probability. Two strategies of power allocation are considered: *power allocation with and without posture state information*. Simulation results verify the accuracy of the analysis and demonstrate that: 1) power allocation making use of the posture information can reduce the energy consumption; 2) within a possible range of the channel quality in WBAN, cooperative communication is more energy efficient than direct transmission only when the path loss between the transmission pair is higher than a threshold; and 3) for most of the typical channel quality due to the fixed transceiver locations on human body, cooperative communication is effective in reducing energy consumption.

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Dedication

For my family, who offered me unconditional love and support throughout the course of this thesis.

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Abbreviations

AF	Amplify-and-Forward
AWGN	Additive White Gaussian Noise
BER	Bit Error Rate
DF	Decode-and-Forward
DT	Direct Transmission
ECG	Electrocardiogram
EEG	Electroencephalogram
MAC	Medium Access Control
MIMO	Multiple-Input-Multiple-Output
MRC	Multiple-Relay Cooperation
NACK	Negative Acknowledgement
PDA	Personal Digital Assistant
PEP	Packet Error Probability
PHY	Physical Layer
QoS	Quality-of-Service
SAR	Special Absorption Ratio
SNR	Signal-to-Noise-Ratio
SRC	Single-Relay Cooperation

SpO2	Saturation of Peripheral Oxygen
TDMA	Time Division Multiple Access
UWB	Ultra Wide-Band
WBAN	Wireless Body Area Network
WSN	Wireless Sensor Network

Chapter 1

Introduction

Wireless communication technologies have undergone explosive growth since the end of the last century, and more and more advanced communication technologies have been deployed to provide the most enjoyable communications for people than ever expected. The increasing use of wireless technologies and the advances in electronics have empowered the development of wireless body area network (WBAN).

A WBAN consists of a number of nodes, placed on and/or around, and/or implanted in the human body, which can communicate with each other through wireless links. In addition, WBAN also has the capability to connect with other wireless networks, such as WiFi and cellular networks. With WBAN, the sensor node can continuously monitor the real-time physiological parameters such as the temperature, blood pressure, heart rate, electrocardiogram (ECG), electroencephalogram (EEG), respiration rate, and SpO2-level [1], and provide feedback to the user or medical personnel. Further, the actuator node in WBAN can act as a drug delivery system. For example, the actuator can start the injection of predetermined dose of insulin when a sudden drop of glucose is detected for diabetes patients. With the wireless nature of the network and the wide variety of sensors/actutators, WBAN provides a greater physical mobility for a patient [2], and the connectivity for the elderly in managing their daily life and medical conditions [3].

Under the circumstance of an aging society with tremendously increasing healthcare expenses, many countries thrill to make use of WBAN technology to improve the healthcare quality and lower relevant cost [4]. In addition to healthcare service, WBAN is also a promising technology to be found in the domain of consumer electronics, athletic training, workplace safety, secure authentication and safeguarding of uniformed personnel [5, 6].

With its myriad applications, the research of WBAN has received extensive attention from both the academia and the industry recently. Several research groups and commercial vendors have already been developing the first prototypes of WBAN. For example, WBAN is deployed for rapid disaster response in the CodeBlue project at Harvard University [7]; a complete end-to-end mHealth platform for ambulant patient monitoring is designed in the European MobiHealth project [8]; and a full platform for the ubiquitous multimedia applications of WBANs is developed in the German BASUMA project[9]. Since November 2007, the IEEE 802.15 tasking group 6 has been formed to define the physical layer (PHY) and medium access control (MAC) standard for WBAN [10].

One of key issues of these research activities is to design communication protocols to realize the diverse applications. Although the techniques from wireless sensor networks (WSNs) and ad hoc networks could be employed in WBAN, protocols designed for these networks are not well suited due to the typical properties of WBAN. In this thesis, we investigate the energy efficiency of cooperative communications in WBAN with the constraints of target outage probability, which are tailored to the WBAN applications.

1.1 Wireless Body Area Network

WBAN supports both medical and nonmedical applications with diverse application requirements. The nodes in the network can be sensors/acutators or personal devices. For

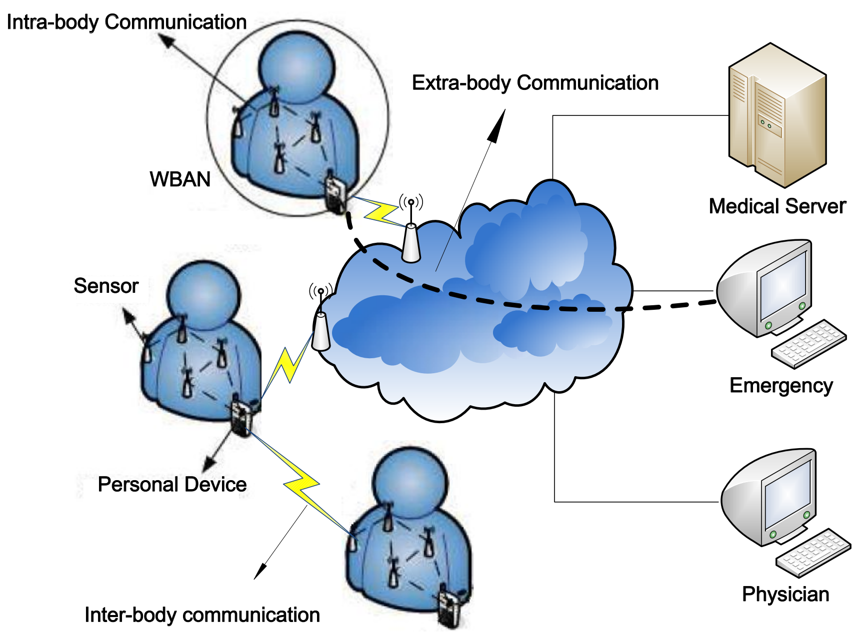

Figure 1.1: Architecture of WBAN.

the sake of clarity, the communications for WBAN can be categorized into three parts: intra-body communication, extra-body communication, and inter-body communication. The intra-body communication controls the information handling on the body among sensors/actutators and personal devices; the extra-body communication ensures the connection between a WBAN and other heterogeneous networks; and the inter-body communication deals with the information exchange among different WBANs. A typical architecture of WBAN is show in Fig. 1.1. Depending on the applications, the nodes in WBAN may communicate with a on-body coordinator, which can be implemented in a PDA, through intra-body communication; or these nodes may communicate to a gateway through which they are connected to a local or wide area network.

Accordingly, WBAN has medical and nonmedical traffic in the network. The medical traffic includes the data generated from continuous waveform sampling of biomedical signals, monitoring of vital signal information, and low rate remote control of medical devices; while non-medical traffic covers video, audio, and data transfer. Compared to WSN and ad hoc network, WBAN has the following unique features:

1. *Limited energy resources:* Most nodes are battery-driven and have no chance to recharge or change battery during the lifetime (up to several years or even decades for the implanted nodes). Further, these nodes have small form factor (often less than 1 cm^3 [4]). Therefore, the energy resources and thus the computational power and available memory of the nodes are limited.

2. *Ultra low transmit power and high path loss:* To avoid negative impact of the electromagnetic radiation and satisfy the requirements of the regulated special absorption ratio (SAR), ultra low transmit power is desirable in WBAN. On the other hand, since the propagation of the waves takes place in or on the human body, wireless signals in WBAN experience a much higher path loss than those in free space.

3. *Frequent change of network topology:* Due to the body posture/movement, the nodes in WBAN can move relatively to each other, and thus the network topology may change frequently.

4. *Dynamic QoS Requirements:* With heterogonous traffic, WBAN needs to support temporally differentiated QoS requirements. In normal case, medical traffic can tolerant delay for sensing data with low duty cycle . On the other hand, if an emergency health situation arises, the life-critical signals along with the aforementioned sensing data should be transmitted with the least delay.

1.2 Motivation and Research Issues

The development of WBAN brings a number of research challenges such as interoperability, scalability, reliability, QoS, and energy efficiency to the design of communication protocols. As we mentioned, the energy resources are very constrained in WBAN. Utilizing energy efficient communication protocols to maximize the network lifetime is important for WBAN applications. Reducing transmit power can be a potential approach. Note that, to avoid negative impact of electromagnetic radiation on human body, it is critical to keep a low transmit power in WBAN. However, the path loss in WBAN is usually larger than 50dB [11], causing severe attenuation on wireless signals, and thus, without sufficient transmit power the link quality is very likely to be deteriorated. Recently, it is observed that, with 1mW transmit power at 2.4GHz, the on-body (off-body) links of WBAN are intermittently disconnected up to 14.8% (14.9%) of the time when people sleep on bed [12]. As such, the network topology of WBAN could be frequently partitioned [13]. Further, the data packets in WBAN mostly consist of medical information with the demands of high reliability and low delay. As a result, how to design communication protocols to ensure an end-to-end reliable communication with the least energy consumption becomes a key challenge in WBAN.

Cooperative communications have the advantage of spatial diversity, thus improving both link reliability and energy efficiency [14, 15]. The power consumption with cooperation in wireless sensor network is studied in [14]. It is shown that, for a large distance separation between the source and destination, cooperative transmission is more energy efficient than direct transmission. The energy efficiency of cooperative communication is further illustrated in the clustered wireless sensor networks in [15], and similar results are revealed. Motivated by these researches, we are interested in the use of cooperative communications in WBAN and the associated performance in terms of energy efficiency.

1.3 Organization of Thesis

The reminder of this thesis is organized as follows. Chapter 2 provides a background on cooperative communications and their applications in WBAN. In Chapter 3, the system model is described. The analysis of outage performance is presented in Chapter 4. The energy consumption minimization is studied in Chapter 5. Simulation results are given in Chapter 6. Chapter 7 summarizes our research conclusions and gives the future work.

Chapter 2

Background

Cooperative communications are termed as that, multiple nodes with only one antenna can collaborate to exploit the spatial diversity of the traditional multiple-input multiple-output (MIMO) techniques by forming a virtual antenna array [16]. Cooperative communications can provide both diversity and spatial multiplexing gains [17]. Specifically, for a cooperative communication with diversity order d, the outage probability can be made to decay like $1/SNR^d$ at high signal-to-noise-ratio (SNR), in contrast to the SNR^{-1} for the direct transmission.

Due to the flexibility of cooperative communications, a number of cooperation strategies are developed to satisfy the requirements of their specific applications. For example, depending on the number of relays to participate in cooperation, cooperative communication could be single-relay based or multiple-relay based; and the relay selection might be opportunistic/probabilistic [18, 19] or deterministic [20, 21, 22]. For a specific relay selection, the relaying strategy can be fixed, selective or incremental [16]. Moreover, dynamic power and bandwidth allocation is able to be incorporated into the cooperation strategies to further improve the system performance [19, 23]. Other advantages of cooperative communications may be found such as high data rate, low transmit power, and efficient use of network resources [24]. With these advantages, cooperative communication could be a potential technique to tackle the energy efficiency problem in WBAN.

2.1 Related Work

There have been several researches on the energy efficiency of cooperative communications. Without considering the extra energy consumed in transmit/receive circuit, cooperative communications can consume less transmit power compared to direct and multihop transmission [18]. In an energy-constrained network such as WSN, the extra energy consumption is important [14]. Taking this into consideration, the energy efficiency of cooperative MIMO in WSN is investigated in [14] and further studied in [15] for the clustered wireless sensor networks. Their researches show that, compared to direct transmission, cooperative communication is more energy efficient for a large distance separation between the source and the destination. The similar argument has been also revealed when studying the single-relay and multiple-relay cooperation in [25].

A WBAN is initially assumed as a single-hop star network [26]. However, according to [27, 28], it is realized that the use of multihop communications could lead to a more energy efficient and reliable network topology. Furthermore, multihop cooperation and relaying schemes are discussed in [29] to prolong the network lifetime of WBAN. A follow-up study in [30] proposes a spanning tree protocol (CICADA) for multihop WBAN. In [31], a gossiping data routing protocol is devised to cope with both high node mobility and poor link quality in the network. The data packet scheduling and optimal transmit power are studied in [32] for multihop links among in-body and on-body nodes. Beacon-enabled TDMA MAC with relay transmission is investigated in [33]. For a beacon-free network, a cooperative preamble-sampling protocol (PS-MAC) is developed by the authors of [34]. However, no cooperation diversity is exploited in these communication protocols.

The cooperative diversity in WBAN is first introduced in [35], where the spatial diversity gain is analyzed in a two-relay assisted transmission link. In [36], cooperative transmission is employed for communications between the on-body nodes and the off-body gateway. Compared to non-cooperative transmission, cooperative transmission (single-relay) can significantly reduce the bit error rate (BER) and prolong the system lifetime. Further, for a specific BER, cooperative transmission saves transmit energy consumption up to 20%. The packet error probability (PEP) for direct, two-hop, and single-relay cooperative transmission are investigated respectively in [37]. The authors employ an on-body channel model, where the path loss is independent with the transmitter-receiver distance. It is shown that, under the condition that all transmitter-receiver pairs use the same transmit power and have identical path loss, direct transmission outperforms two-hop transmission in terms of PEP. On the other hand, the single relay cooperative transmission has less PEP than direct transmission. Although these studies demonstrate that cooperative communication can be effectively implemented in the WBANs, the performance analysis of its energy efficiency is still an open issue.

2.2 Thesis Contribution

In this thesis, we investigate the energy efficiency of cooperative communications in a WBAN. The main contributions of this thesis are as follows. First, we carry out a detailed analysis on the outage performance of three transmission schemes that could be implemented in WBANs, i.e., direct transmission, single-relay cooperation, and multi-relay cooperation. Secondly, to minimize the energy consumption, we study the problem of optimal power allocation with the constraint of targeted outage probability. We consider two power allocation strategies: *power allocation with and without posture information*. To fairly compare the energy consumption between cooperative and noncooperative transmissions, we consider not only transmit energy but also transmitter/receiver circuit energy, which was not considered in [29, 36]. Thirdly, the impact of posture/movement of human body on the wireless link is considered in the analysis and exploited in the power allocation. Finally, through simulation, we demonstrate that how energy efficiency is affected by the transmit power allocation, the relay location, the number of relays and the magnitudes of path loss in different posture states. Our extensive simulation results indicate that: 1) power allocation making use of the posture information can reduce the energy consumption; 2) within a possible range of the channel quality in WBAN, cooperative communication is more energy efficient than direct transmission only when the path loss between the transmission pair is higher than a threshold; and 3) for a practical WBAN, cooperative communication in most cases is effective in reducing energy consumption.

Chapter 3

System Model

3.1 Characteristics of Wireless Channel in WBANs

A typical WBAN is shown in Fig. 3.1, where the nodes (i.e., nodes 2-14 in the figure) transmit data to a central node (i.e., nodes 1 in the figure), which acts as a gateway to other wireless networks, such as WiFi or Cellular network. The propagation of wireless signals in body area communications experiences fading due to diffraction, reflection, energy absorption, and shadowing by body and clothes [11]. Generally, the fading (i.e., the large-scale and small-scale fading) depends on the location of the transceiver on/in human body, the posture/movement of human body, and the working frequency. Research on on-body channel model shows that the large-scale fading referred to as the path loss can be approximated by the Friis formula [38]. The path loss for a fixed transmission pair varies significantly depending on the body posture, and its variation can be as large as 22.2dB [11]. On the other hand, compared to other distributions such as Rayleigh, Rice, Weibull, and Nakagami-m, the Lognormal distribution provides the best fit for the small-scale fading in the WBANs [38]. Therefore, provided a posture state i, when the source node s sends a signal to its destination node d, the received SNR (in dB) at the destination can

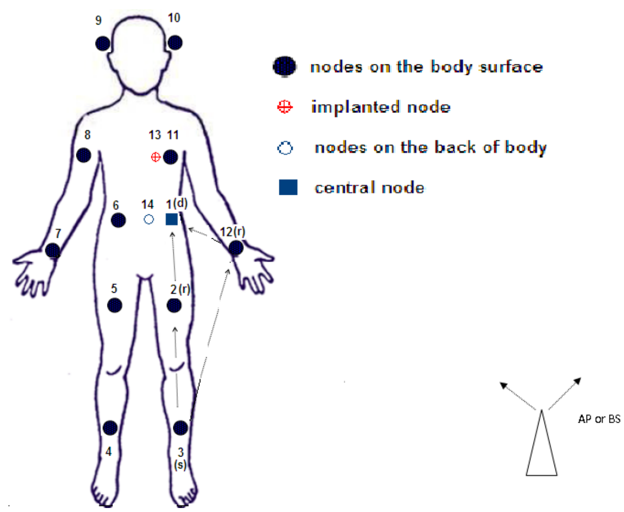

Figure 3.1: A wireless body area network.

be given by

$$\gamma_{sd|i} = P_{s,i} - PL_i^{sd} - X_{\sigma_i^{sd}} - N_0 \tag{3.1}$$

where $i = 1, 2, \ldots, N$, N is the total posture state number, and N_0 is the power of the additive white Gaussian noise (AWGN) at the receiver. In Eq. (3.1), $P_{s,i}$ is the transmit power of the source node, PL_i^{sd} is the path loss between the source and the destination, and $X_{\sigma_i^{sd}} \backsim \mathcal{N}(0, \sigma_i^{sd})$ [39] is the channel attenuation due to the small-scale fading. Notice that the posture states can be modeled as a Markov chain process and each state has a steady state probability π_i [40].

3.2 Transmission Schemes

It is reasonable to assume that all nodes transmit over orthogonal timeslots so that no interference is considered in the sequel. For a data packet transmission, we consider three transmission schemes that could be implemented in the WBANs, direct transmission, single-relay cooperation, and multi-relay cooperation. For the cooperative transmission, we adopt a two-timeslot transmission. In the first timeslot, the source node sends a data packet to the destination, while the neighbor nodes overhear the transmission. In case of the failed reception at the destination, the destination node feeds back a negative acknowledgement (NACK). Then, in the second timeslot, for the single-relay cooperation, only a predefined neighbor named relay node retransmits the data packet if it successfully received the packet in the previous timeslot; on the other hand, for the multi-relay cooperation, an instantaneous optimal relay which once decoded the packet and is of the best channel condition to the destination is selected to forward the packet to the destination. Due to the potential hardware constraints on a node in WBAN, no data combination is employed in cooperative transmission. Further, the links among nodes are independent, and the channel gains and posture states do not change within one date-packet transmission.

Chapter 4

Outage Analysis

Due to the hostile propagation environment, digital transmission over a wireless channel can be very challenging. To study the energy efficiency of wireless transmission in WBAN, the specific QoS requirements tailored for the applications should be taken into account. In this thesis, to satisfy the rigorous requirement for a reliable transmission, we consider outage probability as the QoS metric, which is defined as the probability of the received SNR (γ) falling below a certain threshold (β) [25], i.e.,

$$P_O = Pr(\gamma < \beta). \tag{4.1}$$

In the following, we analyze the outage probability of three transmission schemes case by case.

4.1 Direct Transmission (DT)

Given a posture state i, the outage probability with direct transmission can be derived based on Eq. (3.1) as follows,

$$\begin{aligned}
P_{O|i}^{D} &= Pr(\gamma_{sd|i} < \beta) \\
&= Pr(P_{s,i}^{D} - PL_i^{sd} - X_{\sigma_i^{sd}} - N_0 < \beta) \\
&= Pr(P_{s,i}^{D} - PL_i^{sd} - \beta - N_0 < X_{\sigma_i^{sd}}) \\
&= \frac{1}{\sqrt{2\pi}\sigma_i^{sd}} \int_{-\infty}^{0} exp[-\frac{(t-(P_{s,i}^{D} - PL_i^{sd} - \beta - N_0))^2}{2(\sigma_i^{sd})^2}]dt \\
&= Q(\frac{P_{s,i}^{D} - PL_i^{sd} - \beta - N_0}{\sigma_i^{sd}}) \qquad (4.2)
\end{aligned}$$

where $P_{s,i}^{D}$ is the transmit power of the source in posture state i when direct transmission is utilized, $Q(\cdot)$ is the Q-function defined as $Q(x) = \frac{1}{\sqrt{2\pi}} \int_x^\infty e^{-t^2/2}dt$. For notational simplicity, we define $F(x, y, z) = Q(\frac{x-y-\beta-N_0}{z})$.

4.2 Single-Relay Cooperation (SRC)

The outage occurs when the link between the source and the destination, and the link between the source (or destination) and the relay are in outage. Therefore, given a posture state i, the outage probability of single-relay cooperation is

$$\begin{aligned}
P_{O|i}^{S} &= Pr(\gamma_{sd|i} < \beta)Pr(\gamma_{sr|i} < \beta) + Pr(\gamma_{sd|i} < \beta) \\
&\quad \times Pr(\gamma_{sr|i} \geq \beta)Pr(\gamma_{rd|i} < \beta) \\
&= F(P_{s,i}^{S}, PL_i^{sd}, \sigma_i^{sd})F(P_{s,i}^{S}, PL_i^{sr}, \sigma_i^{sr}) + F(P_{s,i}^{S}, PL_i^{sd}, \sigma_i^{sd}) \\
&\quad \times (1 - F(P_{s,i}^{S}, PL_i^{sr}, \sigma_i^{sr}))F(P_{r,i}^{S}, PL_i^{rd}, \sigma_i^{rd}) \qquad (4.3)
\end{aligned}$$

where $\gamma_{mn|i}$ and PL_i^{mn} are respectively the SNR of the transmission link from the nodes m to n and the path loss between these two nodes in posture state i, and σ_i^{mn} is the standard deviation of variable $X_{\sigma_i^{mn}}$ which denotes the small-scale fading of the link between the nodes m and n, $m, n \in \{s, d, r\}$, r is the relay; $P^S_{s,i}$ and $P^S_{r,i}$ are respectively the transmit power of the source and the relay in posture state i for single-relay cooperation.

4.3 Multiple-Relay Cooperation(MRC)

For the multi-relay cooperation, the outage performance relates to the strategy of relay selection. Consider a cooperative transmission with K potential relays. Let D_l denotes the decoding subset with l relays. Nodes in D_l must successfully receive the data packet from the source in the first timeslot. Then, the optimal relay is defined as the one in D_l and has the best channel condition with the destination, i.e., $r^* = \arg\max_{r\in D_l} \gamma_{rd|i}$. Similar to the single-relay cooperation, given a posture state i, the outage probability of multi-relay cooperation of interest can be calculated as follows,

$$\begin{aligned}
P^M_{O|i} &= Pr(\gamma_{sd|i} < \beta)Pr(D_l = \emptyset|i) + Pr(\gamma_{sd|i} < \beta)Pr(D_l \neq \emptyset|i)Pr(\gamma_{r^*d|i} < \beta) \\
&= Pr(\gamma_{sd|i} < \beta)\prod_{r=1}^{K} Pr(\gamma_{sr|i} < \beta) + Pr(\gamma_{sd|i} < \beta)\sum_{l=1}^{K}\sum_{D_l} \\
&\quad \prod_{r\in D_l} Pr(\gamma_{sr|i} \geq \beta)\prod_{r\notin D_l} Pr(\gamma_{sr|i} < \beta)\prod_{r\in D_l} Pr(\gamma_{rd|i} < \beta) \\
&= Pr(\gamma_{sd|i} < \beta)\prod_{r=1}^{K}\{Pr(\gamma_{sr|i} \geq \beta)Pr(\gamma_{rd|i} < \beta) + Pr(\gamma_{sr|i} < \beta)\}
\end{aligned} \tag{4.4}$$

where the last equation holds because of the multinominal equality [21]

$$\prod_{r=1}^{K}(a_k + b_k) = \sum_{l=0}^{K}\sum_{|D_l|=l, D_l\subseteq\{1,\ldots,K\}}\prod_{r\in D_l} a_k \prod_{r\notin D_l} b_k. \tag{4.5}$$

Eq. (4.4) can also be rewritten as

$$\begin{aligned}
P^M_{O|i} = F(P^M_{s,i}, PL^{sd}_i, \sigma^{sd}_i)\prod_{r=1}^{K}\{&(1 - F(P^M_{s,i}, PL^{sr}_i, \sigma^{sr}_i)) \\
&\times F(P^M_{r,i}, PL^{rd}_i, \sigma^{rd}_i) + F(P^M_{s,i}, PL^{sr}_i, \sigma^{sr}_i)\}
\end{aligned} \tag{4.6}$$

where $P_{s,i}^{M}$ and $P_{r,i}^{M}$ are respectively the transmit power of the source and relays in posture state i for multiple-relay cooperation.

In summary, the average outage probability of each aforesaid transmission scheme can be given by

$$P_O^t = \sum_{i=1}^{N} \pi_i \cdot P_{O|i}^t, \ t \in \{D, S, M\} \tag{4.7}$$

where D, S and M represent the direct transmission, the single-relay cooperation and the multiple-relay cooperation, respectively.

Chapter 5

Energy Consumption Minimization

We adopt the energy model used in [15], where for a single-link transmission the overall consumed energy per bit includes three parts: the transmitter circuit energy consumption per bit, the receiver circuit energy consumption per bit, and the transmitting energy consumption per bit, denoted respectively by E_{ct}, E_{cr}, and E_t. Without loss of generality, we assume all nodes in WBAN consume the same E_{ct} and E_{cr}, and the targeted transmission rate is R_b bits/s. Then, the transmitting energy consumption per bit can be derived by [15]

$$E_t = \frac{10^{P_t/10}}{R_b} \tag{5.1}$$

where P_t is the transmit power of a sending node in dB.

Given posture state i, we can find the overall energy consumption per bit for each of the three transmission schemes, respectively.

For the direct transmission,

$$E^D_{tot|i} = E^D_{s,i} + E_{ct} + E_{cr} \tag{5.2}$$

where $E^D_{s,i} = \frac{10^{P^D_{S,i}/10}}{R_b}$.

For single-relay cooperation, the energy composition can be calculated by considering three possible events: a successful data delivering from the source to the destination in the first timeslot, a failed data delivering from the source to the relay and destination in the first timeslot, and a failed data delivering from the source to the destination but a successful data delivering from the source to the relay. Thus, we have

$$\begin{aligned}
E^S_{tot|i} &= (E^S_{s,i} + E_{ct} + 2E_{cr})Pr(\gamma_{sd|i} \geq \beta) \\
&\quad + (E^S_{s,i} + E_{ct} + 2E_{cr})Pr(\gamma_{sd|i} < \beta)Pr(\gamma_{sr|i} < \beta) \\
&\quad + (E^S_{s,i} + E^S_{r,i} + 2E_{ct} + 3E_{cr})Pr(\gamma_{sd|i} < \beta)Pr(\gamma_{sr|i} \geq \beta) \\
&= (E^S_{s,i} + E_{ct} + 2E_{cr})[1 - F(P^S_{s,i}, PL^{sd}_i, \sigma^{sd}_i)] \\
&\quad + (E^S_{s,i} + E_{ct} + 2E_{cr})F(P^S_{s,i}, PL^{sd}_i, \sigma^{sd}_i)F(P^S_{s,i}, PL^{sr}_i, \sigma^{sr}_i) \\
&\quad + (E^S_{s,i} + E^S_{r,i} + 2E_{ct} + 3E_{cr})F(P^S_{s,i}, PL^{sd}_i, \sigma^{sd}_i) \\
&\quad \times [1 - F(P^S_{s,i}, PL^{sr}_i, \sigma^{sr}_i)]
\end{aligned} \tag{5.3}$$

where $E^S_{s,i} = \frac{10^{P^S_{s,i}/10}}{R_b}$ and $E^S_{r,i} = \frac{10^{P^S_{r,i}/10}}{R_b}$. Since the energy consumption for a NACK is usually much smaller than that for a data-packet transmission, for analysis simplicity, we omit the energy consumption for the NACK.

Similarly, the energy composition for multi-relay cooperation can be calculated by

$$
\begin{aligned}
E^M_{tot|i} &= [E^M_{s,i} + E_{ct} + (K+1)E_{cr}]Pr(\gamma_{sd|i} \geq \beta) \\
&\quad + [E^M_{s,i} + E_{ct} + (K+1)E_{cr}]Pr(\gamma_{sd|i} < \beta)Pr(D_l = \emptyset|i) \\
&\quad + \sum_{r=1}^{K}\{[E^M_{s,i} + E^M_{r,i} + 2E_{ct} + (K+2)E_{cr}] \\
&\quad \times Pr(\gamma_{sd|i} < \beta)Pr(r = r^*|i)\} \\
&= [E^M_{s,i} + E_{ct} + (K+1)E_{cr}](1 - F(P^M_{s,i}, PL^{sd}_i, \sigma^{sd}_i)) \\
&\quad + [E^M_{s,i} + E_{ct} + (K+1)E_{cr}]F(P^M_{s,i}, PL^{sd}_i, \sigma^{sd}_i) \\
&\quad \times \prod_{r=1}^{K} F(P^M_{s,i}, PL^{sr}_i, \sigma^{sr}_i) + \sum_{r=1}^{K}\{[E^M_{s,i} + E^M_{r,i} + 2E_{ct} \\
&\quad + (K+2)E_{cr}]F(P^M_{s,i}, PL^{sd}_i, \sigma^{sd}_i)Pr(r = r^*|i)\}
\end{aligned} \tag{5.4}
$$

where $E^M_{s,i} = \frac{10^{P^M_{s,i}/10}}{R_b}$, $E^M_{r,i} = \frac{10^{P^M_{r,i}/10}}{R_b}$. $Pr(r = r^*|i)\}$ is the probability that the relay r is selected as the best relay, and can be calculated as follows (see Appendix A),

$$
\begin{aligned}
Pr(r = r^*|i) &= \int_{-\infty}^{\infty} \frac{1}{\sqrt{2\pi}\sigma^{rd}_i} \exp[-\frac{(t - (P^M_{r,i} - PL^{rd}_i - N_0))^2}{2(\sigma^{rd}_i)^2}] \\
&\times [1 - F(P^M_{s,i}, PL^{sr}_i, \sigma^{sr}_i)] \\
&\times \prod_{r\prime=1, r\prime\neq r}^{K} \{Q(\frac{P^M_{r\prime,i} - PL^{r\prime d}_i - N_0 - t}{\sigma^{r\prime d}_i})[1 - F(P^M_{s,i}, PL^{sr\prime}_i, \sigma^{sr\prime}_i)] \\
&+ F(P^M_{s,i}, PL^{sr\prime}_i, \sigma^{sr\prime}_i)\}dt.
\end{aligned} \tag{5.5}
$$

Therefore, the average energy consumption of each aforesaid transmission scheme can be obtained by

$$
E^t_{tot} = \sum_{i=1}^{N} \pi_i \cdot E^t_{tot|i}, \; t \in \{D, S, M\}. \tag{5.6}
$$

To improve the energy efficiency of the transmission in WBAN, we compare two strategies for allocating power among the transmission nodes in the network: *power allocation* *with and without posture state information.* The objective is to minimize the average energy consumption in Eq. (5.6). To provide a reliable transmission, we constrain the power allocation by satisfying a pre-defined outage threshold, i.e., $P_O^t \leq P_{out}^*$, $t \in \{D, S, M\}$, P_{out}^* is the outage threshold. We discuss the two strategies in the following separately. Notice that the optimal power allocation in both strategies needs the knowledge of channel statistics in different posture states.

5.1 Power Allocation With Posture Information

In this strategy, for a data transmission, the energy consumption minimization is achieved through allocating different power to a transmitting node in different posture states. For each transmission scheme, the optimal transmit power is derived by solving the following optimization problems respectively. Then the minimum energy consumption for each transmission scheme can be derived by substituting the corresponding optimal transmit power to Eq. (5.1)-(5.6).

(a) Direct transmission:

$$\begin{aligned} &\text{minimize} && E_{tot}^D \\ &\text{subject to} && P_O^D \leq P_{out}^* \\ &\text{variable} && P_{s,i}^D; \qquad\qquad i = 1, \ldots, N. \end{aligned} \tag{5.7}$$

(b) Single-relay cooperation:

$$\begin{aligned} &\text{minimize} && E_{tot}^S \\ &\text{subject to} && P_O^S \leq P_{out}^* \\ &\text{variable} && P_{s,i}^S, \quad P_{r,i}^S; \qquad i = 1, \ldots, N. \end{aligned} \tag{5.8}$$

(c) Multiple-relay cooperation:

$$\begin{aligned}
&\text{minimize} && E_{tot}^{M} \\
&\text{subject to} && P_O^M \leq P_{out}^* \\
&\text{variable} && P_{s,i}^M, \quad P_{r,i}^M; \qquad i = 1, \ldots, N; \\
& && \qquad\qquad\qquad\quad r = 1, \ldots, K.
\end{aligned} \tag{5.9}$$

5.2 Power Allocation Without Posture Information

In this strategy, the transmitting node always utilizes a fixed transmit power for all posture states. We derive the optimal transmit power by solving the following optimization problems and then calculate the minimum energy consumption for each transmission scheme, respectively.

(a) Direct transmission:

$$\begin{aligned}
&\text{minimize} && E_{tot}^{D} \\
&\text{subject to} && P_O^D \leq P_{out}^* \\
& && P_{s,i}^D = P_s^D; \qquad i = 1, \ldots, N \\
&\text{variable} && P_s^D
\end{aligned} \tag{5.10}$$

where P_s^D is the transmit power of the source for all posture states in direct transmission.

(b) Single-relay cooperation:

$$
\begin{aligned}
\text{minimize} \quad & E_{tot}^{S} \\
\text{subject to} \quad & P_O^S \le P_{out}^{*} \\
& P_{s,i}^{S} = P_s^S; \qquad i = 1, \ldots, N \\
& P_{r,i}^{S} = P_r^S; \qquad i = 1, \ldots, N \\
\text{variable} \quad & P_s^S, \quad P_r^S
\end{aligned} \tag{5.11}
$$

where P_s^S and P_r^S are the transmit power of the source and that of the relay for all posture states in single-relay cooperation.

(c) Multiple-relay cooperation:

$$
\begin{aligned}
\text{minimize} \quad & E_{tot}^{M} \\
\text{subject to} \quad & P_O^M \le P_{out}^{*} \\
& P_{s,i}^{M} = P_s^M; \qquad i = 1, \ldots, N \\
& P_{r,i}^{M} = P_r^M; \qquad i = 1, \ldots, N \\
& \qquad\qquad\qquad\quad r = 1, \ldots, K \\
\text{variable} \quad & P_s^M, \quad P_r^M; \qquad r = 1, \ldots, K
\end{aligned} \tag{5.12}
$$

where P_s^M and P_r^M are the transmit power of the source and that of the relays for all posture states in multiple-relay cooperation.

Chapter 6

Simulation Results

In this section, we compare the energy efficiency among different transmission schemes with the two power allocation strategies. In the simulation, the average noise power and the required SNR threshold are set as $N_0 = -100$ dB and $\beta = 10$ dB, respectively. The values of the transmitter circuit energy consumption per bit and the receiver circuit energy consumption per bit are obtained from [27], where $E_{ct} = 16.7$ nJ/bit and $E_{cr} = 36.1$ nJ/bit. The transmission rate is set as $R_b = 200$ kbit/s, and the outage threshold is set as $P^*_{out} = 10^{-4}$. The steady state probability of the postures are calculated based on the data in [40], where the transition probability among six postures (i.e., sit, sit-reclining, lying-down, standing, walking, and running) are measured. For simplicity, only two posture states are considered in the simulation: sit for posture state one and standing for posture state two; and their steady state probabilities in the simulation are $\pi_1 = 0.49$ and $\pi_2 = 0.51$, respectively. We assume the variances of the small-scale fading for any links in the two posture states are $\sigma_1 = 0.6$ and $\sigma_2 = 2.5$ [11], respectively. To compare the energy consumption between non-cooperation and cooperation, we define energy efficiency as the reduced energy consumption (in percentage) due to cooperative transmission. We perform simulations for 10^6 runs and obtain the data by averaging all the simulation results.

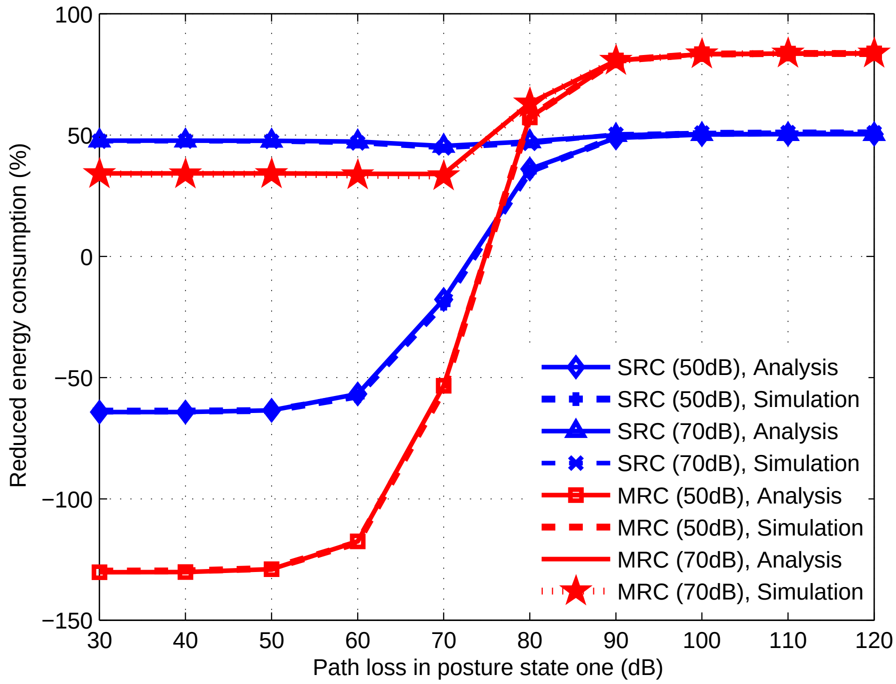

Figure 6.1: Energy efficiency.

6.1 Energy Efficiency

The analytical and simulation results of energy efficiency with the strategy of *power allocation with posture state information* is shown in Fig. 6.1. Here, we fix the path loss of posture state two, and vary the path loss of posture state one in a typical potential range from 30 to 120 dB [41]. In the simulation, we find that the simulated outage probabilities always satisfy the targeted outage probability. This is because that the energy consumption is minimized with the constraint of the target outage probability in the power allocation strategy for each transmission scheme. From Fig. 6.1, it can be seen that whether the cooperative transmission can improve energy efficiency or not depends on the path loss

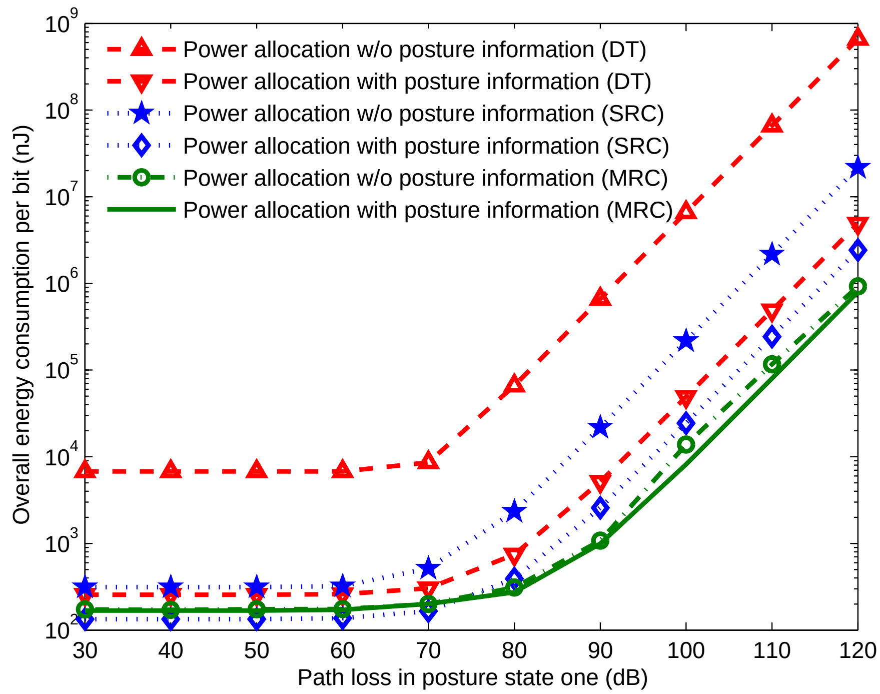

Figure 6.2: The comparison of average energy consumption per bit between the two power allocation strategies.

between a source and a destination. When $PL_2^{sd} = 70$ dB, cooperation is always more energy efficient than non-cooperation; however, when $PL_2^{sd} = 50$ dB, cooperation is more energy efficient only if the path loss of posture state one (PL_1^{sd}) is larger than a threshold. Further, we can see that multi-relay cooperation can consume more energy than single-relay cooperation if the path loss is small. This is because that, the more the number of the relays, the larger the amount of energy consumed in receiver circuit. Therefore, when the channel condition is good, it is better to utilize less relays for energy efficiency.

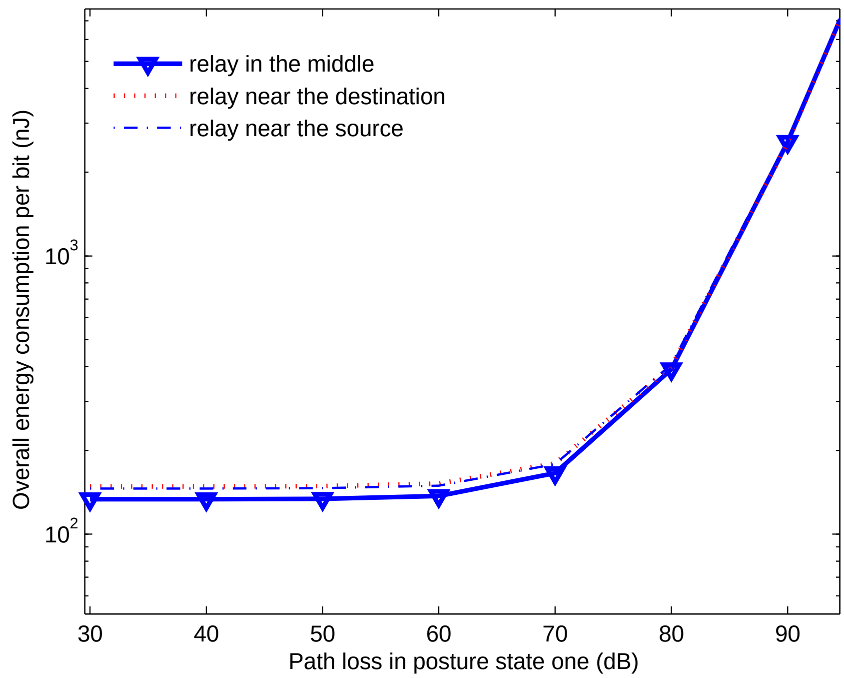

Figure 6.3: Energy consumption for different relay selections

6.2 Power Allocation With and Without Posture Information

In Fig. 6.2, we compare the performance between the two power allocation strategies. Here, we fix $PL_2^{sd} = 70$ dB. From the figure, we can see that the strategy of *power allocation with posture state information* is better than the strategy of *power allocation without posture state information*. However, the performance gap decreases as the number of the relay nodes increases. In addition, direct transmission with the strategy of *power allocation with posture state information* outperforms single-relay cooperation with the strategy of *power allocation without posture state information*. Therefore, it is important to utilize posture state information when designing a power allocation scheme in WBAN.

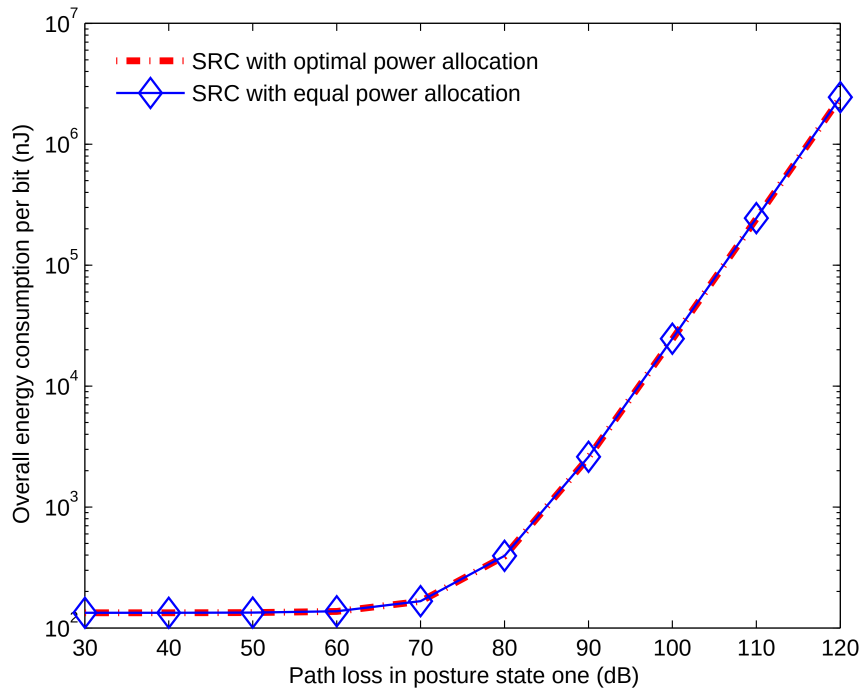

Figure 6.4: Equal power allocation

6.3 Relay Selection

Fig. 6.3 sows the energy consumption for different relay selection. We compare the energy consumption for three relay locations: relay in the middle between the source and destination, relay near the source, and relay near the destination. Here, we still fix $PL_2^{sd} = 70$ dB and vary the PL_1^{sd} from 30 dB to 120 dB . From Fig. 6.3, It can be seen that selecting the relay in the middle is more energy efficient. In this case, equal power allocation between the source and relay is nearly optimal, as shown in Fig. 6.4.

Fig. 6.5 shows the probability of relay transmission in cooperative communications. It can be seen that, the larger path loss between the source and destination, the more chances that the relay transmission is adopted. Further, for multiple-relay cooperation, the probability of the relay transmission is always higher than that in single-relay cooperation.

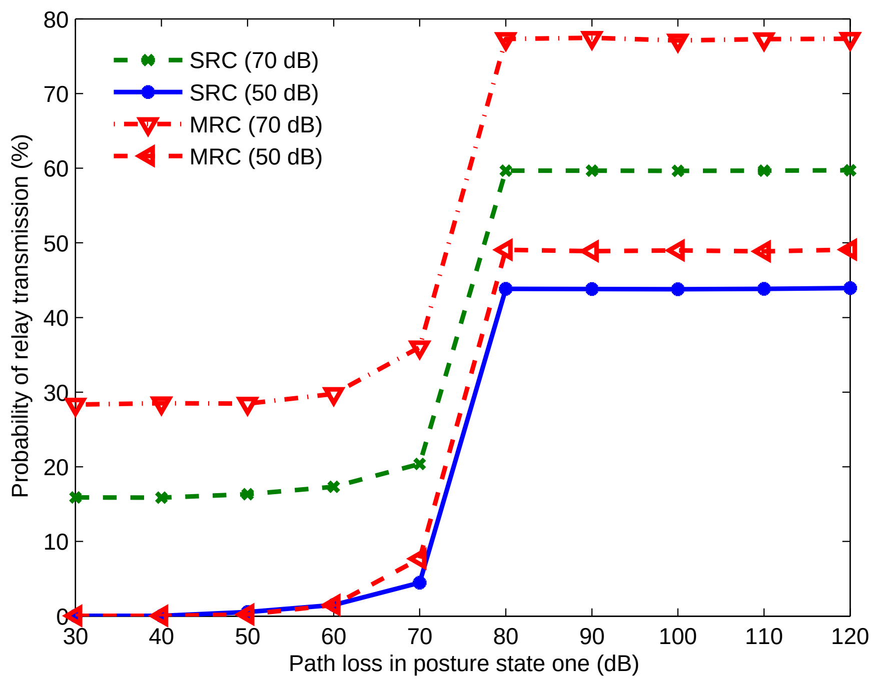

Figure 6.5: Probability of relay transmission

This is because that, the more the number of relays, the higher probability that one of the relays can decode the data packets from the source.

6.4 Best Relay Selection

For multiple-relay cooperation, to verify the accuracy of our analysis on the probability that a relay is selected as the best relay, we set up a simulation as follows. The path loss between the source and destination is $PL^{sd} = 70$ dB with the distance L. Two relays, r_1 and r_2, are placed between the source and destination. The distance from the source to r_1 is $c \cdot L$, where $c \in [0.1, 0.5]$ is the real value, and the distance from the source to r_2 is $(1 - c) \cdot L$. The transmit power of both relays is set as -23.9897 dB, while the transmit power of the source is set as -24.2185 dB. For each calculation, we run the simulation for

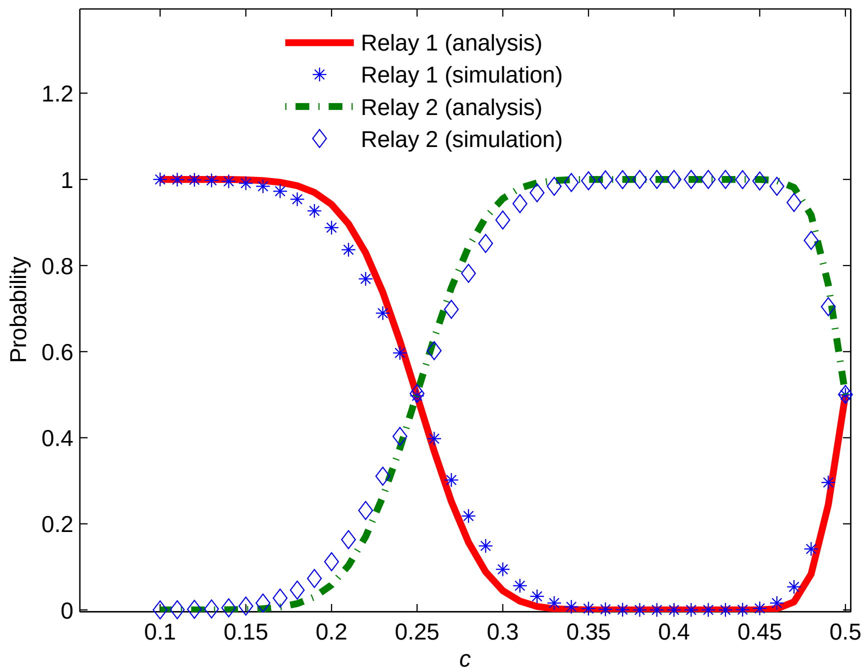

Figure 6.6: Probability of a relay selected as the best relay

10^6 times. As shown in Fig 6.6, it can be seen that the simulation results match with the analytical results.

6.5 Energy Consumption for Nodes With Typical Locations

Based on the path loss parameter shown in table 6.1 [11], we also assess the average energy consumption. Fig. 6.7 shows the average energy consumptions for nodes with typical locations in the WBAN shown in Fig. 3.1. It can be seen that there is only one node (i.e., the node in the left wrist) that cooperative communication fails to improve its energy efficiency. In other words, cooperative communication in most cases is effective in reducing

Table 6.1: Path loss of the nodes in different postures (dB)

Location	L-ear	R-ear	L-wrist	R-wrist	R-waist	L-ankle	R-ankle
Standing	73.8	70.4	61.4	70.9	74.3	76.4	68.3
Sit	62.3	72.1	65.6	76.3	74.7	79.8	75.7

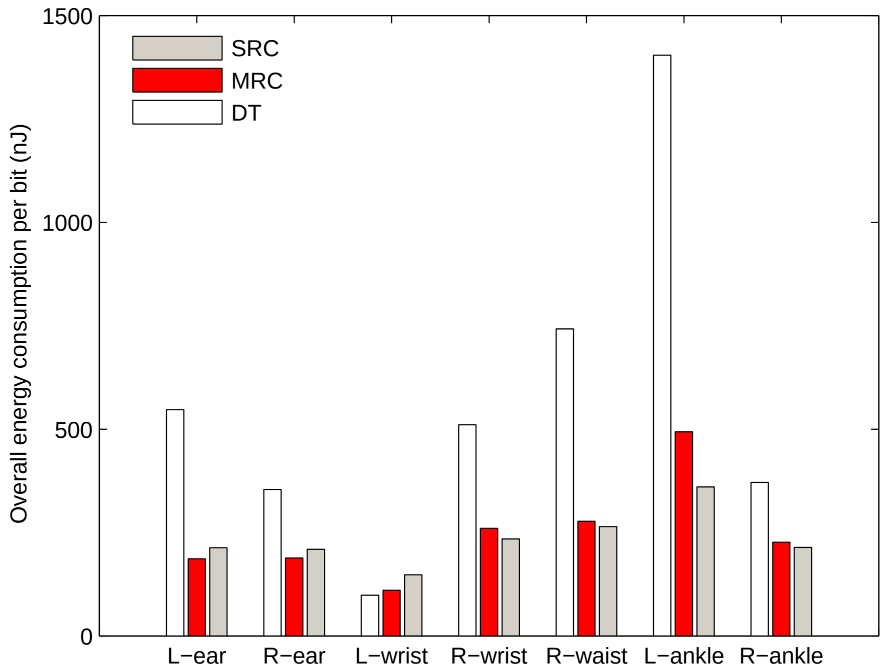

Figure 6.7: Average energy consumption for nodes with typical positions in WBAN. (L=left, R=right)

energy consumption. The reason that cooperative communication fails to improve its energy efficiency for the node in the left wrist, is that the path loss between this node and the central node has small path loss.

Chapter 7

Conclusion

In this thesis, we have studied on the issue of improving energy efficiency for WBAN. Three transmission schemes are compared in the thesis, i.e., direct transmission, single-relay cooperation, and multi-relay cooperation. For each one of them, we analyze its outage performance and study the optimal power allocation with the constraint of target outage probability. Simulation results demonstrate that cooperative communication can improve energy efficiency for WBAN. Further, the posture state information is important when designing a power allocation scheme for WBAN.

7.1 Future Work

For the future work, based on cooperative communications, we can design a MAC protocol tailored for WBAN, and evaluate the corresponding energy consumption of the network. Although there are some cooperative MAC protocols (such as CoopMAC [42]) designed for wireless ad hoc networks and WSN, they are not adaptable to WBAN due to the unique challenges in WBAN. Specifically, to save energy, most medical nodes go to sleep when they do not have data packets to transmit. Each node has its own duty cycle due to its specific function. In this case, the relay nodes need to wake up intentionally to participate cooperation. The frequent sleep/wakeup of nodes increases the dynamics of network topology, and complicates the process of relay selection in cooperative communications. Further, the signaling overhead and its energy cost for relay selection could be significant for the energy-limited networks. How to leverage both cooperative diversity and low duty cycle transmission to achieve high energy efficiency is a key issue for the design of MAC protocol in WBAN.

Adaptive power allocation/control is another issue for the future work. In our research, we have demonstrated the importance to utilize posture state information when designing a power allocation scheme in WBAN. Direct transmission with the strategy of *power allocation with posture state information* outperforms single-relay cooperation with the strategy of *power allocation without posture state information*, in terms of energy efficiency. Posture-based power control is also investigated in [43, 44, 31] for WBAN. These researches show that power allocation/control with posture state information can improve both the link reliability and energy efficiency. From a network perspective, however, other network parameters, such as priority, queue size and packet delay, also need to be considered when implementing the strategies of power allocation/control for WBAN. Additionally, for ultra wide-band (UWB) communication, a promising technology for WBAN, power allocation/control is crucial to mitigate multiuser interference within WBAN or among multiple coexisting networks.

Finally, dynamic resource allocation is an important issue for the future research on WBAN. According to [10], to support multimedia communication, the data rate of a WBAN ranges from 1 Mb/s to 10 Mb/s. The QoS requirements for medical and multimedia communication are intrinsically different. For example, medical communication normally has higher priority, while multimedia communication has higher bandwidth demands. How to efficiently allocate limited bandwidth to support differentiated QoS is an issue in WBAN. On the other hand, to reduce interference, each WBAN can work in different frequency. However, when many WBANs coexist in an area, the number of channels is limited. To support the coexistence of WBANs, a MAC superframe is divided into active and inactive period [41]. Since the traffic load in each WBAN changes dynamically, the resource allocation, such as channel selection/assignment and the coordination of active period, is critical to ensure the overall throughput performance and inter-network fairness among independent WBANs.

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APPENDICES

Appendix A

Derivation of Eq. (5.5)

In order to calculate the probability that a relay r is selected as the best relay, let $f_{\gamma_{rd|i}}(t)$ denote the probability density function (pdf) of $\gamma_{rd|i}$. Since $\gamma_{rd|i} = P_{r,i}^M - PL_i^{rd} - X_{\sigma_i^{rd}} - N_0$ and $X_{\sigma_i^{rd}} \backsim \mathcal{N}(0, \sigma_i^{rd})$, we have

$$f_{\gamma_{rd|i}}(t) = \frac{1}{\sqrt{2\pi}\sigma_i^{rd}} \exp[-\frac{(t - (P_{r,i}^M - PL_i^{rd} - N_0))^2}{2(\sigma_i^{rd})^2}]. \tag{A.1}$$

Let D_l' denote the decoding subset excluding the relay r, i.e., $D_l' = D_l - \{r\}$. Then the probability $Pr(r = r^*|i)$ can be calculated as follows,

$$
\begin{aligned}
Pr(r=r^*|i) &= Pr(\gamma_{sr|i} \geq \beta) \sum_{l=1}^{K-1} \sum_{D'_l} Pr(\gamma_{rd|i} \geq \gamma_{r'd|i}, r' \in D'_l) Pr(D'_l) \\
&= Pr(\gamma_{sr|i} \geq \beta) \sum_{l=1}^{K-1} \sum_{D'_l} \int_{-\infty}^{\infty} f_{\gamma_{rd|i}}(t) \prod_{r' \in D'_l} Pr(\gamma_{r'd|i} \leq t) \\
&\quad \times \prod_{r' \in D'_l} Pr(\gamma_{sr'|i} \geq \beta) \prod_{r' \notin D'_l} Pr(\gamma_{sr'|i} < \beta) dt \\
&= Pr(\gamma_{sr|i} \geq \beta) \int_{-\infty}^{\infty} f_{\gamma_{rd|i}}(t) \sum_{l=1}^{K-1} \sum_{D'_l} \prod_{r' \in D'_l} Pr(\gamma_{r'd|i} \leq t) \\
&\quad \times \prod_{r' \in D'_l} Pr(\gamma_{sr'|i} \geq \beta) \prod_{r' \notin D'_l} Pr(\gamma_{sr'|i} < \beta) dt \\
&= Pr(\gamma_{sr|i} \geq \beta) \int_{-\infty}^{\infty} f_{\gamma_{rd|i}}(t) \prod_{r'=1, r' \neq r}^{K} [Pr(\gamma_{r'd|i} \leq t) \\
&\quad \times Pr(\gamma_{sr'|i} \geq \beta) + Pr(\gamma_{sr'|i} < \beta)] dt. \qquad (A.2)
\end{aligned}
$$

The last equation holds because of the multinominal equality [21]. By substituting A.1 to A.2, we have

$$
\begin{aligned}
Pr(r=r^*|i) = \int_{-\infty}^{\infty} & \frac{1}{\sqrt{2\pi}\sigma_i^{rd}} \exp[-\frac{(t-(P_{r,i}^M - PL_i^{rd} - N_0))^2}{2(\sigma_i^{rd})^2}] \\
& \times [1 - F(P_{s,i}^M, PL_i^{sr}, \sigma_i^{sr})] \\
& \times \prod_{r\prime=1, r\prime \neq r}^{K} \{Q(\frac{P_{r\prime,i}^M - PL_i^{r\prime d} - N_0 - t}{\sigma_i^{r\prime d}}) \\
& \times [1 - F(P_{s,i}^M, PL_i^{sr\prime}, \sigma_i^{sr\prime})] \\
& + F(P_{s,i}^M, PL_i^{sr\prime}, \sigma_i^{sr\prime})\} dt. \qquad (A.3)
\end{aligned}
$$