Prediction-based Dynamic Relay Transmission Scheme for Wireless Body Area Networks

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***Abstract*—To support long-term pervasive healthcare services, communications in Wireless Body Area Networks (WBANs) need to be both reliable and energy-efficient. As a cooperative transmission method, relay transmission scheme works effectively in resisting shadowing effect and improving reliability in WBANs. However, the extra energy consumption introduced by relay transmission is very high, which can shorten the lifetime of the whole network. In this paper, temporal and spatial correlation models for on-body channels are first presented to better characterize the slow fading effect of on-body channels. Then a prediction-based dynamic relay transmission (PDRT) scheme that makes full use of the correlation characteristics of on-body channels is proposed. In the PDRT scheme, "when to relay" and "who to relay" are decided in an optimal way based on the last known channel states. Moreover, neither extra signaling procedure nor dedicated channel sensing period is needed. Simulation results show that the PDRT scheme achieves significant performance improvement in energy efficiency, as well as ensuring the transmission reliability.**

***Index Terms*—Wireless Body Area Networks, relay transmission, body area channels, temporal and spatial correlation models, energy efficiency, outage probability.**

I. Introduction

Recently, the continuous development of the emerging Wireless Body Area Network (WBAN) technology has laid a solid foundation for pervasive healthcare services. Due to its ability to support various medical applications in a long-term and unobtrusive fashion, WBAN has made a great contribution to healthcare services by improving service quality, enhancing patient experience and reducing relevant cost. One of the most important challenges for WBAN-based healthcare applications is that the transmission reliability should be well guaranteed since unreliable data delivery will negatively affect the medical monitoring and may even make human life in danger. However, reliability requirement often fails to be achieved in WBANs due to the shadowing effect on the wireless body area channels [1]. Furthermore, since the battery size is very limited for miniaturized WBAN sensor nodes, the energy consumption of sensor nodes should be kept extremely low to support a long-term monitoring without interventions. Therefore, designing a reliable and energy-efficient data transmission strategy for WBAN becomes imperative to promote the advancement of pervasive healthcare services.

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A simple one-hop star topology is widely adopted in WBANs [2]. However, such deployment is not sufficient to achieve WBAN reliability requirement since a strong shadowing effect generated by human body itself may lead to severe attenuation of the signal envelope. For instance, when a patient is sleeping, the average outage probability of WBAN channels is greater than 10% with a standard one-hop star topology [3], indicating that reliability cannot be well guaranteed with such single-link WBAN communications. Although retransmission or variable slot assignment can be adopted to improve reliability, their performance in reliability enhancement is low when the link outage durations are far in excess of WBAN delay requirement, i.e., 125 ms for medical WBANs [4], because nodes can still suffer bad links when they retransmit packets.

As a cooperative communication method, relay transmission scheme exploits spatial diversity to improve communication reliability and is very promising for WBAN communications from the perspectives of performance and complexity [5]. In the relay transmission scheme, packets that are lost due to bad link quality can be retransmitted by relay nodes via other good links. D'Errico *et al.* [6] compared the relay transmission scheme with direct transmission and double-hop transmission schemes and demonstrated the effectiveness of the relay transmission scheme in reducing PER (packet error rate). Maman *et al.* [7] proposed two adaptive TDMA-based MAC protocols, BATMAC and advanced BATMAC, which could automatically mitigate shadowing effect through relaying. However, the energy consumed by a relay node is rather high, i.e., 1.59 and 1.76 times higher than the energy consumed by a sensor node for BATMAC and advanced BATMAC, respectively. Hara *et al.* [8] proposed a cooperative transmission scheme for WBANs by selecting a suitable relay node for each sensor node based on the principle of "low blocking correlation".

Although the desired reliability for WBANs can be achieved by adopting the relay transmission schemes mentioned above, the problem of high energy consumption of relay nodes has not been well investigated. As a result, relay nodes die much faster than sensor nodes. Furthermore, in order to improve comfortableness for

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human body, it is usually recommendable to implement the relaying function into sensor nodes, thus minimizing the number of on-body nodes. Due to the much higher energy consumption of sensor nodes embedded with relaying function, the lifespan of WBANs can be further shortened. Therefore, maximizing the energy efficiency of relay transmission while ensuring the communications reliability is of great importance for pervasive healthcare applications in WBANs.

It is important to note that there is no need to allocate relay nodes to links with good quality. Hence, by relaying for bad links only, energy consumption for relaying can be reduced. Besides, owing to the special structure and movement patterns of human body, choosing different on-body nodes as relay nodes usually leads to distinctive differences in reliability enhancement [6]. Motivated by the above considerations, a prediction-based dynamic relay transmission (PDRT) scheme is proposed in this paper. After fully investigating the characteristics of the dynamic WBAN channels according to the channel measurement results in [9]–[13], we focus on solving the problems of "*when to relay*" and "*who to relay*" for an on-body link based on a novel channel prediction approach, which is able to ensure an optimal allocation of relay nodes. Meanwhile, neither extra signaling procedure nor dedicated channel sensing period is introduced by the proposed scheme as the relay allocation is fully controlled by the coordinator based on the last obtained channel states and is realized through beacon broadcasting. Consequently, the energy consumption and system complexity are further reduced.

The rest of the paper is organized as follows. In Section II, the temporal and spatial correlation models for on-body channels are built. Based on the correlation models, the PDRT scheme is proposed in Section III. In Section IV, we present simulation results to evaluate the performance of the proposed scheme. Finally, concluding remarks are given in Section V.

II. System Models

A. Brief Framework

A WBAN consisting of a coordinator and N wireless on-body sensor nodes indexed from 1 to N is considered in this paper. Due to various human postures and motions, however, the direct links between sensor nodes and the coordinator are often blocked by the human body, which leads to a high PER. Therefore, relay transmission scheme is adopted in order to meet the reliability requirement for WBAN. We assume that all the sensor nodes in the WBAN have the capability of relaying. A basic relay transmission model is illustrated in Fig. 1. The sensor node S_i sends its data to the coordinator (denoted by C), while the sensor node S_j serves as its relay node to increase the packet delivery rate, i.e., S_j listens for the packets sent from S_i and then forwards the received packets to the coordinator for S_i. Moreover, S_i never retransmits the data by itself, and the retransmission is made only by S_j through relaying.

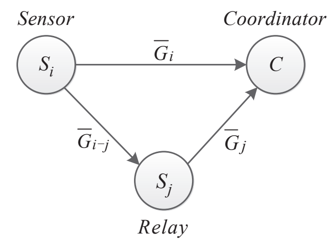

Fig. 1. Relay transmission model

To support the proposed relay transmission scheme, a new TDMA-based MAC superframe structure is presented here. As illustrated in Fig. 2, each superframe is divided into 3 parts: the active-transmit period, the active-forward period and the inactive period. During the active-transmit period, each sensor node transmits the sensed data to the coordinator in its dedicated slots whereas relay nodes, if necessary, listen to their corresponding sensor nodes for data reception. When the active-forward period comes, relay nodes forward the received data to the coordinator in the assigned forwarding slots. During the inactive period, all the sensor nodes are in sleeping mode.

The slot assignment is controlled by the coordinator, and the beacon containing the information about slot assignment is broadcasted to each node. As illustrated in Fig. 2, there are 3 types of slots in the active period of the superframe structure: transmitting slot, listening slot and forwarding slot. Transmitting slots are assigned to sensor nodes for data transmitting whereas listening slots and forwarding slots are assigned to relay nodes for data listening and data forwarding, respectively. Once the transmitting slots are determined, the assignment of listening slot and forwarding slot can be determined according to the optimal relay allocation result. For example, if the m_ith slot is assigned to the sensor node S_i as its transmitting slot, and S_j is allocated to S_i as its optimal relay node, then the m_ith slot is assigned to S_j as its listening slot, and the first available forwarding slot is assigned to S_j for retransmission.

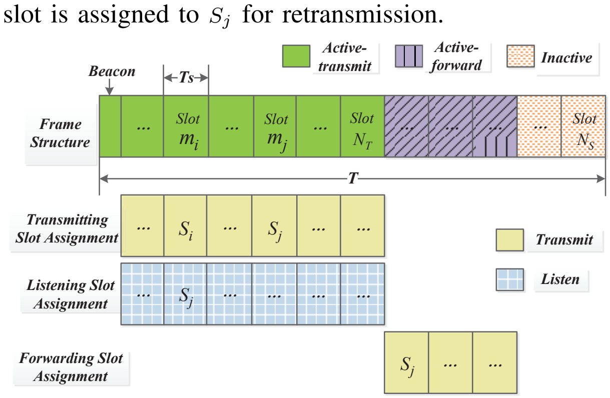

Fig. 2. The proposed TDMA-based MAC superframe structure

B. Temporal Correlation Model for On-body Channels

The long-term average channel gain, denoted by $\bar{G}$, characterizes the slow fading effect of on-body channels which is considered to be a major factor affecting the link reliability. Statistical characteristics of $\bar{G}$ have been studied in [10]–[12] and can be described with a Lognormal distribution:

$$\bar{G}\,|_{\mathrm{dB}} \sim \mathcal{N}(\mu_{\mathbb{S}}, \sigma_{\mathbb{S}}^2) \tag{1}$$

where mean $\mu_{\mathbb{S}}$ and standard deviation $\sigma_{\mathbb{S}}$ directly depend on the specific scenario $\mathbb{S}$, i.e., the positions of transmitting and receiving nodes, human behavior and the environment. In order to predict the future channel behavior based on the last known channel state, a temporal correlation model for on-body channels is investigated. For the convenience of discussion, we neglect the beacon length, and regard $\mathbf{dB}$ and $\mathbf{dBm}$ as the default units for channel gain and signal power, respectively. If one sensor node, namely S_i, sends its data to the coordinator during the m_ith slot of the current superframe with a transmit power of P_t, then the long-term average channel gain of the $S_i - C$ link during this slot can be derived as follows:

$$\bar{G}_i(m_i)\,|_{\mathrm{dB}} = \bar{P}_i(m_i)\,|_{\mathrm{dBm}} - P_t\,|_{\mathrm{dBm}} \tag{2}$$

where $\bar{P}_i$ is the average signal power received by the coordinator and can be obtained immediately from Received Signal Strength Indicator (RSSI) value of received packet. $\bar{G}_i(m_i)$ represents the quality of link $S_i - C$ during the m_ith slot of current superframe. Due to the temporal correlation of slow fading effect in WBANs, the average channel gain during a future slot that is k slots after the m_ith slot, namely $\bar{G}_i(m_i + k)$, can be predicted based on the current channel state $\bar{G}_i(m_i)$. Assuming the scenario is unchanged within a short time period, distributions of $\bar{G}_i(m_i)$ and $\bar{G}_i(m_i + k)$ are identical:

$$\bar{G}_i(m_i)\,|_{\mathrm{dB}} \sim \mathcal{N}(\mu_i, \sigma_i^2),\ \bar{G}_i(m_i + k)\,|_{\mathrm{dB}} \sim \mathcal{N}(\mu_i, \sigma_i^2) \tag{3}$$

where μ_i and σ_i are the mean and standard deviation of $\bar{G}_i$ in some specific scenario, respectively. Their joint distribution can be expressed as follows:

$$(\bar{G}_i(m_i), \bar{G}_i(m_i + k))\,|_{\mathrm{dB}} \sim \mathcal{N}(\mu_i, \mu_i, \sigma_i^2, \sigma_i^2, \rho_i(k)) \tag{4}$$

$$\rho_i(k) = \frac{E\{[\bar{G}_i(m_i) - \mu_i][\bar{G}_i(m_i + k) - \mu_i]\}}{\sigma_i^2}, k = 1, 2, \ldots, K$$

where $\rho_i(k)$ is the correlation coefficient between $\bar{G}_i(m_i)$ and $\bar{G}_i(m_i + k)$ and is unrelated to m_i. In fact, the autocorrelation of on-body channels weakens as the time interval increases, which means $\rho_i(k)$ will decrease with the increase of k. Consequently, there is a temporal correlation coefficient vector for link $S_i - C$, namely, $\boldsymbol{\rho_i} = \begin{pmatrix} \rho_i(1) & \rho_i(2) & \cdots & \rho_i(K) \end{pmatrix}^{\mathrm{T}}$. We call (4) the temporal correlation model for on-body channels that characterizes not only the first-order statistics but also the temporal correlation of on-body channels. We can see the joint distribution is unrelated to the initial time m_i, which is similar to the homogeneity of Markov model mentioned in [1]. Based on (4), we can predict the future channel behavior. Suppose $\bar{G}_i(m_i)$ is already obtained according to (2), the conditional probability density function of $\bar{G}_i(m_i + k)$ can be calculated as:

$$f_{\bar{G}_i(m_i+k)|\bar{G}_i(m_i)}(\bar{G}_i(m_i + k)\,|\bar{G}_i(m_i)) = \frac{f_{\bar{G}_i(m_i),\bar{G}_i(m_i+k)}(\bar{G}_i(m_i), \bar{G}_i(m_i + k))}{f_{\bar{G}_i(m_i)}(\bar{G}_i(m_i))}$$

where $f_{\bar{G}_i(m_i),\bar{G}_i(m_i+k)}$ is the joint probability density function of $\bar{G}_i(m_i)$ and $\bar{G}_i(m_i + k)$, and $f_{\bar{G}_i(m_i)}$ is the probability density function of $\bar{G}_i(m_i)$. By further derivation, the distribution of the random variable $\bar{G}_i(m_i + k)$ for a given $\bar{G}_i(m_i)$ is:

$$\bar{G}_i(m_i + k)\,|_{\mathrm{dB}} \sim \mathcal{N}((1 - \rho_i(k)) \cdot \mu_i + \rho_i(k) \cdot \bar{G}_i(m_i), (1 - \rho_i^2(k)) \cdot \sigma_i^2) \tag{5}$$

C. Spatial Correlation Model for On-body Channels

There may be strong spatial correlations among on-body links due to the unique structure and movement patterns of human body. Suppose that the transmission between the sensor node S_i and the coordinator takes place during the m_ith slot of the active-transmit period and the relay transmission is required, the assigned relay node S_j will listen to S_i during the m_ith slot and retransmit the received data to C during the first available forwarding slot, i.e., the $(m_i + N_x)$th slot, where the positive integer N_x indicates the time interval between the m_ith slot and the first available forwarding slot. The average channel gain for link $S_i - C$, $S_i - S_j$ and $S_j - C$ during the corresponding slots are denoted by $\bar{G}_i(m_i)$, $\bar{G}_{i-j}(m_i)$ and $\bar{G}_j(m_i + N_x)$, respectively. According to (1), the distributions of the above three random variables could be written as:

$$\bar{G}_i(m_i)\,|_{\mathrm{dB}} \sim \mathcal{N}(\mu_i, \sigma_i^2),\ \bar{G}_{i-j}(m_i)\,|_{\mathrm{dB}} \sim \mathcal{N}(\mu_{ij}, \sigma_{ij}^2),$$
$$\bar{G}_j(m_i + N_x)\,|_{\mathrm{dB}} \sim \mathcal{N}(\mu_j, \sigma_j^2)$$

where (μ_i, σ_i), $(\mu_{ij}, \sigma_{ij})$and (μ_j, σ_j) are the mean and standard deviation of $\bar{G}_i$, $\bar{G}_{i-j}$ and $\bar{G}_j$ in the specific scenario, respectively. During the m_ith slot, the data are transmitted via link $S_i - C$ and link $S_i - S_j$ simultaneously, and the correlation between $\bar{G}_i(m_i)$ and $\bar{G}_{i-j}(m_i)$ should be taken into consideration since there may be a spatial correlation between the two links. On the other hand, S_j forwards the received data in the active-forward period, which is N_x time slots later and through a different on-body link. Therefore, for simplicity of analysis, we ignore the correlations between $\bar{G}_j(m_i+N_x)$ and the other two random variables $\bar{G}_i(m_i)$ and $\bar{G}_{i-j}(m_i)$. The joint distribution of $\bar{G}_i(m_i)$ and $\bar{G}_{i-j}(m_i)$ can be expressed as:

$$(\bar{G}_i(m_i), \bar{G}_{i-j}(m_i))\,|_{\mathrm{dB}} \sim \mathcal{N}(\mu_i, \mu_{ij}, \sigma_i^2, \sigma_{ij}^2, \zeta_{ij}) \tag{6}$$

$$\zeta_{ij} = \frac{E\left\{[\bar{G}_i(m_i) - \mu_i][\bar{G}_{i-j}(m_i) - \mu_{ij}]\right\}}{\sigma_i \sigma_{ij}},$$
$$i, j \in \{1, 2, \ldots, N\} \text{ and } j \neq i$$

where ζ_{ij} is the correlation coefficient between $\bar{G}_i(m_i)$ and $\bar{G}_{i-j}(m_i)$ and is unrelated to m_i.

III. The Proposed PDRT Scheme

A. Step 1: When to Relay

Firstly, we need to decide whether it is necessary to allocate a relay node to a sensor node during the next superframe based on the last known channel state. Suppose that sensor node S_i has sent its data to the coordinator during the m_ith slot of the current superframe with a transmit power of P_t. Hence, the m_ith slot of the current superframe is called the current transmitting slot of S_i. According to (2), the average channel gain of the $S_i - C$ link during the current transmitting slot, i.e., $\bar{G}_i(m_i)$, can be easily obtained by the coordinator based on the RSSI value of the received packet. If the n_ith slot of the next superframe is assigned to S_i as its next transmitting slot, which is N_I slots after S_i's current transmitting slot, then the average channel gain of the $S_i - C$ link during this slot, i.e., $\bar{G}_i(n_i)$, can be predicted as follows:

$$\bar{G}_i(n_i)\,|_{\mathrm{dB}} \sim \mathcal{N}((1-\rho_i(N_I))\cdot\mu_i + \rho_i(N_I)\cdot\bar{G}_i(m_i), (1-\rho_i^2(N_I))\cdot\sigma_i^2) \tag{7}$$

The outage probability of the $S_i - C$ link during the next transmitting slot of S_i is given by:

$$Pout_i(n_i) = Prob(\bar{P}_i(n_i) \leqslant \bar{P}^*) = Prob(\bar{G}_i(n_i) + P_t \leqslant \bar{P}^*) = Prob(\bar{G}_i(n_i) \leqslant \bar{G}^*) \tag{8}$$

where $\bar{P}_i(n_i)$ is the average received signal power during S_i's next transmitting slot, $\bar{P}^*$ is the pre-defined receiving power threshold, and $\bar{G}^* = \bar{P}^* - P_t$ is defined as the link outage threshold. According to (8), we know that a link outage takes place when the average received power is lower than $\bar{P}^*$. Thus, $Pout_i(n_i)$ can be calculated as:

$$Pout_i(n_i) = \int_{-\infty}^{\bar{G}^*} f_{\bar{G}_i(n_i)}(\bar{G}_i)d\bar{G}_i = \Phi\Big(\frac{\bar{G}^* - (1-\rho_i(N_I))\cdot\mu_i - \rho_i(N_I)\cdot\bar{G}_i(m_i)}{\sqrt{(1-\rho_i^2(N_I))}\cdot\sigma_i}\Big) \tag{9}$$

where $f_{\bar{G}_i(n_i)}(\bar{G}_i)$ is the probability density function of $\bar{G}_i(n_i)$, and $\Phi(\cdot)$ is the cumulative distribution function of the standard Normal distribution. Once $Pout_i(n_i)$ is predicted, whether to allocate a relay node to the sensor node S_i can be decided through the following strategy:

$$\begin{array}{ll} if\ Pout_i(n_i) > \theta & a\ relay\ node\ is\ needed \\ else & no\ relay\ node\ is\ needed \end{array}$$

where θ is the pre-defined threshold for relay allocation.

B. Step 2: Who to Relay

If it is necessary to relay for the $S_i - C$ link, then the relay node should be carefully selected from the other $N-1$ nodes. Suppose that the sensor node S_j is assigned to S_i as its relay node, we need to investigate the average channel gain of link $S_i - C$ and link $S_i - S_j$ during the next transmitting slot, i.e., $\bar{G}_i(n_i)$ and $\bar{G}_{i-j}(n_i)$. The distribution of $\bar{G}_i(n_i)$ has been investigated in (7), which can be denoted as follows:

$$\bar{G}_i(n_i)\,|_{\mathrm{dB}} \sim \mathcal{N}(\mu_i(N_I), \sigma_i^2(N_I))$$

where $\sigma_i^2(N_I) = (1-\rho_i^2(N_I))\cdot\sigma_i^2$ and $\mu_i(N_I) = (1-\rho_i(N_I))\cdot\mu_i + \rho_i(N_I)\cdot\bar{G}_i(m_i)$. Due to the dynamic strategy, it is very likely that S_j is not selected as the relay node of S_i and is sleeping during S_i's current transmitting slot, which means $\bar{G}_{i-j}(m_i)$ may be unobtainable. Thus, the distribution of $\bar{G}_{i-j}(n_i)$ could be simply considered as:

$$\bar{G}_{i-j}(n_i)\,|_{\mathrm{dB}} \sim \mathcal{N}(\mu_{ij}, \sigma_{ij}^2)$$

where μ_{ij} and σ_{ij} are the mean and standard deviation of $\bar{G}_{i-j}$ in the specific scenario, respectively. According to the spatial correlation model, the joint distribution of $\bar{G}_i(n_i)$ and $\bar{G}_{i-j}(n_i)$ for a given sensor node S_i can be expressed as follows:

$$(\bar{G}_i(n_i), \bar{G}_{i-j}(n_i))\,|_{\mathrm{dB}} \sim \mathcal{N}(\mu_i(N_I), \mu_{ij}, \sigma_i^2(N_I), \sigma_{ij}^2, \zeta_{ij})$$
$$j \in \{1,2,\ldots,N\} \text{ and } j \neq i \tag{10}$$

After receiving the data sent from S_i during the n_ith slot of the next superframe, relay node S_j will forward the data to the coordinator during its forwarding slot, i.e., the $(n_i + N_x)$th slot of the next superframe. Meanwhile, S_j is also a sensor node and periodically transmits the sensed data to the coordinator. If S_j's current transmitting slot is the m_jth slot of the current superframe, which is N_{JI} slots before its forwarding slot, then the average channel gain of the $S_j - C$ link during this slot, i.e., $\bar{G}_j(m_j)$, can be used to predict the average channel gain of the $S_j - C$ link during the forwarding slot:

$$\bar{G}_j(n_i+N_x)\,|_{\mathrm{dB}} \sim \mathcal{N}((1-\rho_j(N_{JI}))\cdot\mu_j + \rho_j(N_{JI})\cdot\bar{G}_j(m_j), (1-\rho_j^2(N_{JI}))\cdot\sigma_j^2) \tag{11}$$

We know that the combined link $(S_i - C \cup S_i - S_j - C)$ is in outage only when the $S_i - C$ link and the $S_i - S_j - C$ link are both blocked. Hence, the outage probability of the combined link can be expressed as follows:

$$Pout_i(j) = Prob\left((\bar{G}_i(n_i) \leqslant \bar{G}^*) \cap (\bar{G}_{i-j}(n_i) \leqslant \bar{G}^*)\right) + Prob\left((\bar{G}_i(n_i) \leqslant \bar{G}^*) \cap (\bar{G}_{i-j}(n_i) > \bar{G}^*) \cap (\bar{G}_j(n_i+N_x) \leqslant \bar{G}^*)\right)$$

Since $\bar{G}_j(n_i+N_x)$ is assumed to be uncorrelated to $\bar{G}_i(n_i)$ and $\bar{G}_{i-j}(n_i)$ in the spatial correlation model, $Pout_i(j)$ can be calculated as follows:

$$Pout_i(j) = \int_{-\infty}^{\bar{G}^*}\int_{-\infty}^{\bar{G}^*} f_{\bar{G}_i(n_i),\bar{G}_{i-j}(n_i)}(\bar{G}_i, \bar{G}_{i-j})d\bar{G}_i d\bar{G}_{i-j} + \int_{\bar{G}^*}^{+\infty}\int_{-\infty}^{\bar{G}^*} f_{\bar{G}_i(n_i),\bar{G}_{i-j}(n_i)}(\bar{G}_i, \bar{G}_{i-j})d\bar{G}_i d\bar{G}_{i-j} \cdot \int_{-\infty}^{\bar{G}^*} f_{\bar{G}_j(n_i+N_x)}(\bar{G}_j)d\bar{G}_j$$

where $f_{\bar{G}_i(n_i),\bar{G}_{i-j}(n_i)}(\bar{G}_i, \bar{G}_{i-j})$ is the joint probability density function of $\bar{G}_i(n_i)$ and $\bar{G}_{i-j}(n_i)$, and $f_{\bar{G}_j(n_i+N_x)}(\bar{G}_j)$ is the probability density function of $\bar{G}_j(n_i+N_x)$. Then the optimal relay allocation strategy can be performed as follows:

$$j^* = \arg\min_j \{Pout_i(j)\,|\, j \in \{1,2,\ldots,N\}, j \neq i\} \tag{12}$$

It is indicated in (12) that the node minimizing the outage probability of the combined link is the optimal relay node. Finally, the coordinator allocates the optimal relay node S_{j^*} to the $S_i - C$ link during the next transmitting slot of S_i. In the PDRT scheme, the optimal relay allocation for the next superframe is performed completely by the coordinator according to the channel states obtained in the current superframe. Therefore, the proposed scheme will not introduce any dedicated channel sensing period or extra signaling procedure, further improving the energy efficiency of relay transmission.

IV. Performance Evaluation of PDRT Scheme

In our simulated monitoring scenario, a common used WBAN setting is adopted. The human body is equipped with 5 sensor nodes which transmit sensed data to the coordinator in a real-time manner and have the function of relaying. The coordinator is placed on Right Hip (RH), and 5 sensor nodes are placed on Chest (CH), Left Wrist (LW), Right Wrist (RW), Left Ankle (LA) and Right Ankle (RA), respectively. Moreover, walking indoor is chosen as the default body movement. Consequently, the parameters of the temporal and spatial correlation models can be determined based on the channel measurement results in [9]–[12], as shown in Table I, II. We set the pre-defined receiving power threshold $\bar{P}^*$ as -85 dBm. And the transmit power P_t is set as -10 dBm, which is the recommended transmit power level for medical devices [14], so the link outage threshold $\bar{G}^*$ is -75 dB.

The TDMA-based MAC superframe structure illustrated in Fig. 2 is adopted in our simulation. The slot length T_S and the superframe length T are set as 5 ms and 50 ms, respectively. We assume that each sensor node needs only one slot to transmit the sensed data to the coordinator, and the rest 5 slots of the superframe serve as the active-forward period. Although the PDRT scheme can support the variable transmitting slot assignment, the fixed transmitting slot assignment is employed to emphasize the performance enhancement introduced by PDRT scheme rather than variable slot assignment. As shown in Table I, the temporal correlation coefficient vectors for all the links between sensor nodes and the coordinator are considered identical in the walking condition. Only the temporal correlation coefficients within 100 ms are shown due to space limitation. To show the performance of single-link communications, we calculate the outage probabilities of all the links. The outage probabilities of link $S_{LA}-C$, link $S_{RW}-C$ and link $S_{LW}-C$, are all larger than 5%, which means it is necessary to allocate relay nodes to the 3 links to achieve reliable communications.

As shown in Table II, three cases are considered separately, and the parameters of the spatial correlation model are listed accordingly. In each case, relay allocation is only performed for the sensor node S_i, and the other four sensor nodes serve as the potential relay nodes. The relay allocation for multiple sensor nodes is similar and can be realized by simply extending our simulations.

To demonstrate the effectiveness of the proposed PDRT scheme, we compare the performance of the PDRT scheme with the following four schemes:

1) Single-link transmission: the sensor node sends data without retransmission or relaying;
2) Prediction-based retransmission: if the link quality is bad during the next transmitting slot of the sensor node, the sensor node itself will retransmit its data during the active-forward period;
3) Random-selection relay transmission: whether it is necessary to allocate any relay nodes to the sensor node is first decided according to the first step of PDRT scheme; if needed, one randomly selected relay node is allocated to the sensor node;
4) Best-effort relay transmission: whether it is necessary to allocate any relay nodes to the sensor node is first decided; if needed, all the other four nodes are allocated to the sensor node as its relay nodes.

We consider two performance evaluation metrics, i.e., outage probability and relay duty-cycle, which represent the reliability and the energy consumption for relaying, respectively. We define the relay duty-cycle as:

$$\tau_R = \frac{M_R \times R}{M_{Total}} \times 100\%$$

where $M_{Total} = 10,000$ is the total number of simulated superframes, M_R is the number of superframes where relay nodes are necessary for the sensor node, and R is the number of relay nodes allocated to the sensor node each time, i.e., its value is 1 for Random-selection RT and PDRT, and 4 for Best-effort RT. The energy consumption for relaying is expressed as a percentage τ_R, thus we do not care the transmitting and receiving power consumption of on-body nodes which depends on the specific physical layer technique. Since the energy consumption for data transmitting is identical for each

TABLE I

Temporal correlation model parameters for on-body links in walking condition

Link $S_i - C$	(μ_i, σ_i)	Outage Probability	$\boldsymbol{\rho_i}$ $(\rho_i(1) \cdots \rho_i(20))$
$S_{LA}-C$	(-63.694, 10.736)	14.61%	0.99 0.98 0.96 0.94
$S_{RA}-C$	(-61.496, 7.835)	4.24%	0.92 0.90 0.88 0.86
$S_{LW}-C$	(-63.694, 10.736)	41.15%	0.85 0.84 0.83 0.82
$S_{RW}-C$	(-59.968, 9.537)	5.75%	0.80 0.78 0.77 0.76
$S_{CH}-C$	(-58.439, 3.692)	0	0.75 0.74 0.73 0.72

TABLE II

Spatial correlation model parameters for on-body links in walking condition

Case	Node S_i (Sensor)	Node S_j (Relay)	(μ_{ij}, σ_{ij}) $(S_i - S_j)$	$\zeta_{ij}(S_i - C, S_i - S_j)$
1	S_{LA}	S_{LW}	(-59.707, 9.659)	-0.5
		S_{RW}	(-64.449, 10.718)	0.1
		S_{RA}	(-61.079, 10.788)	0
		S_{CH}	(-64.736, 10.076)	0.7
2	S_{RW}	S_{LW}	(-72.301, 8.182)	-0.2
		S_{LA}	(-64.449, 10.718)	-0.4
		S_{RA}	(-59.707, 9.641)	0.3
		S_{CH}	(-62.938, 10.423)	0.7
3	S_{LW}	S_{LA}	(-59.707, 9.641)	0.3
		S_{RW}	(-72.301,8.182)	-0.2
		S_{RA}	(-64.449, 10.718)	-0.4
		S_{CH}	(-62.938, 10.423)	0.7

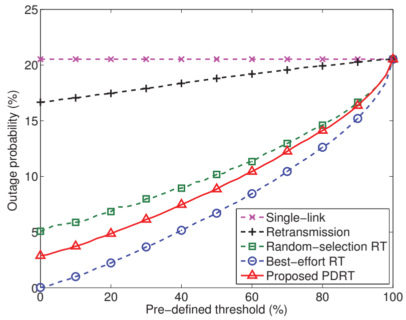

Fig. 3. The outage probability under walking condition with the superframe length of 50 ms

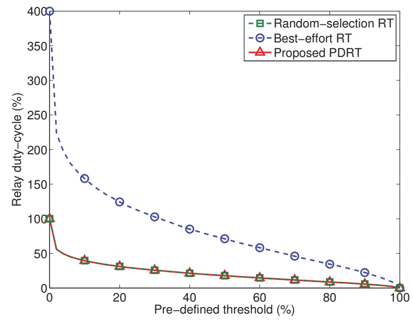

Fig. 4. The relay duty-cycle under walking condition with the superframe length of 50 ms

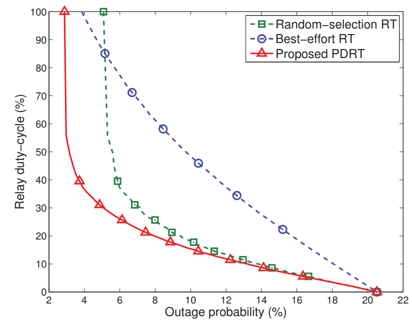

Fig. 5. Performance comparison among the three cooperative schemes (walking, 50 ms)

scheme, the energy consumption for relaying can represent the energy efficiency of a relay transmission scheme, i.e., a larger τ_R indicates lower efficiency.

We first evaluate the proposed PDRT scheme in terms of outage probability and relay duty-cycle averaged for the three cases mentioned in Table II. It can be seen from Fig. 3 that the outage probability increases with the increase of θ since relay and retransmission take place only when the predicted outage probability is higher than θ. Although Best-effort RT achieves the lowest outage probability due to its 4-relay allocation strategy, its relay duty-cycle is three times larger than those of the other schemes as illustrated in Fig. 4, which is unacceptable for practical WBAN applications. For the schemes with same energy consumption, the PDRT scheme provides best performance because it exploits both temporal and spatial correlations of on-body channels. In the case where θ is 1, relay nodes are never allocated, so the relay duty-cycle is reduced to 0 whereas the outage probability reaches a same value of 20.5% for all the schemes.

To verify the advantage of PDRT scheme in terms of energy efficiency, we show the relay duty-cycle as a function of outage probability for the three cooperative schemes. As shown in Fig. 5, a lower outage probability is achieved with a higher relay duty-cycle for all the schemes, showing that the reliability can be improved by increasing the energy consumption for relaying. Furthermore, the performance curve of the PDRT scheme is the lowest, indicating that the PDRT scheme outperforms other schemes in energy efficiency. It is because "when to relay" and "who to relay" are decided in an optimal way based on the channel states in the PDRT scheme.

V. Conclusions

In this paper, we first establish the temporal and spatial correlation models for on-body channels to better understand and utilize the channel characteristics. Then, a prediction-based dynamic relay transmission scheme for cooperative WBAN communications is proposed to guarantee the desired link reliability in an energy-efficient way. In the proposed scheme, "when to relay" and "who to relay" are decided based on the last known channel states in an optimal manner. Consequently, the energy efficiency of relay transmission is greatly improved.

Acknowledgment

This work is supported by the National Natural Science Foundation of China (Grant No. 61202406), the USTC Grand Master Professor Funds (ZC9850290097), the Fundamental Research Funds for the Central Universities of China (WK2100230002) and the USTC Funds for Youth Scholars (KA2101020001).

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