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Cooperative Communication Transmission Based on Dynamic Slot Allocation for Wireless Body Area Networks

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Abstract: For the reliability problem of data transmission in wireless body area network, this paper proposes a reliable and efficient cooperative communication transmission strategy, which introduces dynamic time slot allocation mechanism into wireless body area network cooperative communication transmission strategy to ensure data reliability transmission and save energy consumption. In this paper, a Markov model representing the time-varying characteristics of wireless body area network channel is used to the channel model. According to the initial state information of the channel, the data transmission slot is dynamically adjusted. On this basis, the outage probability of direct transmission and relay cooperative transmission is compared and analyzed. The simulation results show that the proposed strategy not only guarantees the reliable transmission, but also satisfies the change of data rate. It can effectively reduce the outage probability of transmission under the changeable wireless body area network channel conditions, thus providing higher reliability performance and energy efficiency.

Keywords: Wireless body area network, Data reliability transmission, Dynamic time slot allocation, Cooperative communication.

1. INTRODUCTION

In recent years, with the improvement of people's living standards and the rapid development of wireless communication technology, Wireless Body Area Networks (WBAN) has broad application prospects in the field of modern medical and health. Wireless body area network is a human-centered wireless sensor network [1-3]. It usually consists of a central node as a coordinator and a number of sensor nodes to monitor human health information. In wireless body area network, data information is transmitted centrally by human body, which will suffer loss and fading caused by human body and other wireless channels. The shadow effect caused by the movement of the human body and the shielding of the clothes [4], as well as multi-path effect caused by the absorption of signals by body tissues and the environment around human body, seriously reduces the quality of communication links, making transmission reliability the primary consideration in wireless body area networks.

Relay transmission has the advantage of spatial diversity and is therefore commonly used to improve the reliability of wireless communication links. In [6], an energy-aware routing protocol for cooperative communication in wireless body area networks is proposed, which performs relay cooperative communication according to energy and connection problems to forward packets. It also provides its data transmission via relay when the coordinator's battery is running out. The performance analysis of cognitive cooperative communication in wireless body area networks is studied, and the effects of factors such as the distance between primary and secondary nodes and the number of auxiliary nodes used in the network on network capacity and system performance are discussed in [7-8]. Although these studies have shown that cooperative communication can effectively improve the reliability of data transmission, cooperative communication also increases the consumption of receiving power while using relay transmission, which limits the energy efficiency to a certain extent. Another idea to improve the performance of wireless body area network communication links is dynamic transmission slot allocation approach, which has the characteristics of high energy efficiency. In [9], a time division multiple access based variable scheduling method is proposed to reduce the loss of data transmission, but it allows only one slot to be allocated to one node, which may not meet the traffic demand of nodes with relatively high data rate.A quality of service (QoS) based media access control (MAC) protocol is proposed to deal with channel fading in wireless body area networks in [10]. However, it is not enough to mitigate the effect of fading only by utilizing the nature of the channel. When link transmission is in deep fading condition, the reliability of adjusting the transmission slot of nodes is not improved. Therefore, this paper proposes a reliable and efficient cooperative communication transmission strategy, which introduces the dynamic time slot allocation mechanism into the wireless body network cooperative communication transmission strategy, which saves energy consumption while ensuring data reliability transmission.

2. SYSTEM MODEL

The model of the wireless body area network system considered in this paper is shown in Fig. 1. Assuming that each sensor node has the function of relay and forwarding, the source signals collected by the sensor nodes can be transmitted directly to the central node or cooperatively from the relay to the central node. When the communication link directly transmitted by the source node to the destination node encounters strong fading and the signal is in error, the relay node with better link condition can be selected for data transmission, thereby ensuring the reliability of the transmission. The source node sends the data packet to the destination node, and the neighboring relay node can overhear the transmission. If the destination node at the receiving end correctly receives the information, the relay node that feeds back an acknowledgement information (ACK) while listening to the information remains idle. Otherwise, a negative acknowledgement (NACK) is fed back and the relay node receives the information.

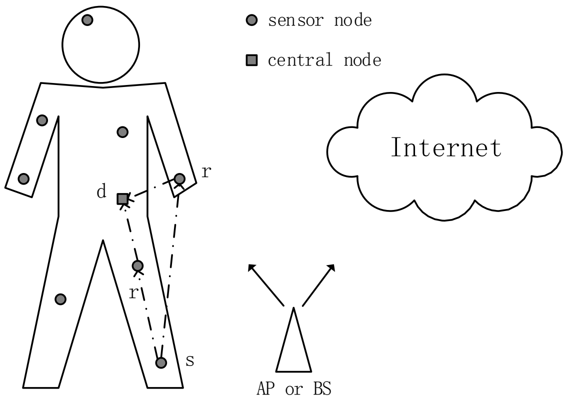

Fig. 1 Wireless body area network model

According to the recommendations of the IEEE 802.15.6 working group, this paper uses Markov Channel Model to model the wireless channel between sensor nodes and central nodes. Assuming that there are two states of "good" and "bad" in the wireless channel link, the data packet can be successfully transmitted in the good channel state and fail in the bad channel state. Then the Markov transition probability matrix of two states is expressed as P,

$$P = \begin{bmatrix} 1-P_{BG} & P_{BG} \\ P_{GB} & 1-P_{GB} \end{bmatrix} \tag{1}$$

where, P_{GB} is the transition probability from good state to bad state. It represents the probability that the node succeeds in transmitting in the previous slot and fails in transmitting in the current slot. Correspondingly, P_{BG} is the transition probability from bad state to good state. Because of the heterogeneous location and mutual movement of sensor nodes, each link may have different transfer probability matrices. The state of a link in a slot is $X(0)$. When the link is in a bad state, its value is 0, and when it is in a good state, its value is 1. The probability that it will be in a good state after τ slots is given by

$$\begin{aligned} P(\tau) &= \begin{bmatrix} 1-X(0) & \mathrm{X}(0) \end{bmatrix} \cdot (P)^{\tau} \cdot \begin{bmatrix} 0 \\ 1 \end{bmatrix} \\ &= \begin{cases} \dfrac{\mathrm{P_{BG}}}{\mathrm{Q}} - \dfrac{\mathrm{P_{BG}}(1-\mathrm{Q})^{\tau}}{\mathrm{Q}} & \mathrm{X}(0)=0 \\ \dfrac{\mathrm{P_{BG}}}{\mathrm{Q}} + \dfrac{\mathrm{P_{GB}}(1-\mathrm{Q})^{\tau}}{\mathrm{Q}} & \mathrm{X}(0)=1 \end{cases} \end{aligned} \tag{2}$$

where $Q = P_{BG} + P_{GB}$. It can be seen that when $X(0)$ equals 0 or 1 respectively, $P(\tau)$ is a monotonic increasing function or a monotonic decreasing function. When τ goes to infinite, $P(\tau)$ approaches $P_{BG}/Q = P_{BG}/(P_{BG}+P_{GB})$, which represents the long-term transmission probability of the link.

3. COOPERATIVE COMMUNICATION TRANSMISSION STRATEGY

3.1 Adjustment of time slots

In The initial channel condition of the link can be obtained by using Markov channel model. According to the initial channel state information, the slot allocation of node transmission can be determined. The specific steps of slot allocation are as follows:

Step 1: Determine the slot transmission interval allocated by the node in the superframe

The initial channel conditions available to the system are the transmission results of the slots allocated in the previous superframe, and the central node estimates the channel conditions of the nodes in the upcoming superframe. In this paper, the nodes with good or bad initial channel conditions are represented by sets $GOOD = \{i \mid X_i(0) = 1\}$ and $BAD = \{i \mid X_i(0) = 0\}$, respectively. Due to the monotonicity of $P(\tau)$, it can be found that the transmission probability of nodes in set $GOOD$ will decrease with time, while the transmission probability of nodes in set BAD will increase with time. Therefore, this paper adjusts the slot transmission interval of nodes by threshold method. Assuming that TH_i is the transmission success rate threshold required by node i, in order to ensure reliable transmission, the transmission probability of sensor node i in its allocated slot should not be less than that threshold. Thus, the transmission probability reliability constraint of node i is given by

$$p(D_i + x_i) \geq TH_i \Rightarrow x_i \leq a_i \quad i \in GOOD \tag{3}$$

$$p(D_i + y_i) \geq TH_i \Rightarrow y_i \geq b_i \quad i \in \mathrm{BAD} \tag{4}$$

where D_i is the number of slots that node i passes through after completing its transmission in the previous superframe, x_i and y_i are the number of slots allocated by node i in the upcoming superframe, and a_i and b_i represent the boundaries of slots allocated by node i in the upcoming superframe.

According to the expression, when the initial channel condition of node i is in good state, the number of slots allocated to node i in the upcoming superframe should not exceed a_i, otherwise, when the initial channel condition of node i is in bad state, the number of slots allocated to node i in the upcoming superframe should not be less than b_i. This means that all slots of node i $(i \in GOOD)$ should be allocated before the a_i slot in the upcoming superframe, and all slots of node i $(i \in BAD)$ should be arranged after the b_i slot in the upcoming superframe to determine the slot transmission interval of the node.

Step 2: Determine the number of slots occupied by nodes in the transmission interval

It is very important to guarantee the long-term service of the system under limited energy in wireless body area networks. This paper only considers the energy consumption during data communication. The number of slots allocated by each node is related to the energy consumption of sensor nodes. Therefore, this paper considers the constraints of the data rate of each node, and dynamically changes the number of slots allocated by the sensor nodes to meet its traffic requirements, while minimizing the total energy consumption of the nodes. Sensor nodes send data to the central node in a specified time slot. When they complete data transmission or when there are no packets to send in the sensor buffer, they will enter a dormant state to save energy. All sensor nodes are awakened at the beginning of the new superframe to update slot allocation information. Accordingly, the corresponding constraints on the data rate of node i is given by

$$Rn_i \geq S_i T \tag{5}$$

$$\sum_{i \in W} n_i \le T \tag{6}$$

where W is a collection of sensor node i in wireless body area network, $i = 1, 2, ..., N$. n_i and S_i are the number of slots allocated by node i and the minimum data rate requirement respectively. R is the transmission rate of radio in wireless body area network. After introducing the slot number n_i allocated by nodes, the reliability constraints proposed above can be also written as

$$\mathrm{n_i} + \sum_{\{j|a_j<a_i\}} \mathrm{n_j} \le \mathrm{a_i} \qquad i \in \mathrm{GOOD} \tag{7}$$

$$\sum_{\{g|a_g \le a_{\max}\}} n_j + \sum_{\{j|b_j<b_i\}} n_j \ge b_i \qquad i \in BAD \tag{8}$$

The above two formulas are the constraints of reliable data transmission under good or bad initial channel conditions. According to formulas (5), (6), (7) and (8), the number of slots allocated by nodes in superframe can be obtained. Because the objective function and constraints are linear, and integer slots are needed, the result of slot allocation is an Integer Linear Programming (ILP) problem that can be effectively solved.

Through the above two steps, slot allocation and slot adjustment of nodes can be completed. This paper then discusses the transmission scheme of cooperative communication and its outage probability calculation.

3.2 Outage analysis

Due to the bad propagation environment of wireless body area network, the signal transmission on wireless channel will be very challenging. In order to meet the strict requirement of reliable transmission, this paper regards interruption probability as a measure of quality of service (QoS), and it is defined as the probability that the signal-to-noise ratio (SNR) (γ) of the receiver is lower than a certain threshold (β), i.e.,

$$P_O = \Pr(\gamma < \beta) \tag{9}$$

In this paper, the outage probability of three transmission schemes, namely direct transmission, single relay cooperative transmission and multiple relay cooperative transmission , in wireless body area network is analyzed and studied theoretically.

Direct Transmission (DT)

First, consider the case of direct transmission. The condition for interruption of direct transmission is that SNR of receiver is lower than threshold β. According to the received signal model in [11], the SNR (in dB) between the source node and the destination node can be expressed as follows,

$$r_{sd} = P_s - PL^{sd} - X_{\sigma^{sd}} - N_0 \tag{10}$$

where P_s is the transmission power of the source node, PL^{sd} is the path loss of the communication link between the source node and the destination node, and $X_{\sigma^{sd}} \sim N(0, \sigma^{sd})$ is the channel attenuation caused by small-scale fading. N_0 is the power of additive white Gaussian noise at the receiver. The study of body surface channel model shows that PL^{sd} can be further expressed as

$$PL^{sd} = \alpha_1 \log_{10} d + \alpha_2 + S \tag{11}$$

where d is the distance between sensors in centimeters. S is a random number with zero mean and standard deviation obeying lognormal distribution. α_1 and α_2 are constants varying with frequency band. They are - 8.6 and - 20.3 at 2.4 GHz, respectively.

Then the outage probability of direct transmission is

$$P_O^D = \Pr(\gamma_{sd} < \beta) = \Pr(P_s^D - PL^{sd} - X_{\sigma^{sd}} - N_0 < \beta) \tag{12}$$

Since X_σ is a normal distribution of channel attenuation satisfying zero mean, formula (12) can be further expressed as

$$\begin{aligned} P_O^D &= \Pr(\gamma_{sd} < \beta) \\ &= \Pr(P_s^D - PL^{sd} - \beta - N_0 < X_{\sigma^{sd}}) \\ &= \mathrm{Q}(\frac{P_s^D - PL^{sd} - \beta - N_0}{\sigma^{sd}}) \end{aligned} \tag{13}$$

where P_s^D is the transmitting power of the source node signal in the case of direct transmission, $Q(\cdot)$ is a Q-function, which is defined as $Q(x) = 1/\sqrt{2\pi}\int_x^\infty e^{-t^2/2}dt$.

single relay cooperative (SRC)

In cooperative transmission mode, relay is responsible for forwarding information when the destination node cannot receive the information from the source node correctly only in the last allocated slot. When the received signal to noise ratio of the link between source and destination and between source (or destination) and relay is below the threshold, the single relay cooperation will be interrupted, so the outage probability is

$$P_O^S = \Pr(\gamma_{sd} < \beta)\Pr(\gamma_{sr} < \beta) + \Pr(\gamma_{sd} < \beta)\Pr(\gamma_{sr} \ge \beta)\Pr(\gamma_{rd} < \beta) \tag{14}$$

For represent simplicity, define $F(x, y, z) = Q\{(x - y - \beta - N_0)/z\}$, then

$$\begin{aligned} P_O^S &= F(P_s^S, PL^{sd}, \sigma^{sd})F(P_s^S, PL^{sr}, \sigma^{sr}) + \\ &\quad F(P_s^S, PL^{sd}, \sigma^{sd})(1 - F(P_s^S, PL^{sr}, \sigma^{sr}))F(P_r^S, PL^{rd}, \sigma^{rd}) \end{aligned} \tag{15}$$

where γ_{mn} and PL^{mn} are SNR of the transmission link from node m to node n and path loss between the two nodes respectively, while σ^{mn} is the standard deviation of variable $X_{\sigma^{mn}}$, representing small-scale fading of nodes and links between them, $m, n \in \{s, d, r\}$, and r represent relay nodes. P_s^S and P_r^S are the transmission power of source nodes and relay nodes for single relay cooperation, respectively.

Multiple-Relay Cooperative (MRC)

For multi-relay scenarios, it is assumed that there are l reliable relays in the body area network, which are represented by set D_l. When the information sent by the source node to the destination node is interrupted, the relay node R_1 is responsible for forwarding the information to the destination node. If the destination node fails to decode the information correctly, a denial message is still fed back, and the candidate relay node R_2 forwards the information to the destination node, which is repeated until the destination node can receive the information sent by the source correctly or until all the reliable candidate relays fail to forward the information. Similar to single-relay cooperative transmission, the outage probability of multi-relay cooperative transmission can be calculated as follows,

$$\begin{aligned} P_O^M &= \Pr(\gamma_{sd} < \beta)\Pr(D_l = \phi) + \Pr(\gamma_{sd} < \beta)\Pr(D_l \neq \phi)\Pr(\gamma_{r^*d} < \beta) \\ &= \Pr(\gamma_{sd} < \beta)\prod_{r=1}^{K}\{\Pr(\gamma_{sr} \geq \beta)\Pr(\gamma_{rd} < \beta) + \Pr(\gamma_{sr} < \beta)\} \end{aligned} \tag{16}$$

Similarly, the formula can be written as

$$\begin{aligned} P_O^M = F(P_s^M, PL^{sd}, \sigma^{sd})\prod_{r=1}^{K}\{1 - F(P_s^M, PL^{sr}, \sigma^{sr})F(P_r^M, PL^{rd}, \sigma^{rd}) \\ + F(P_s^M, PL^{sr}, \sigma^{sr})\} \end{aligned} \tag{17}$$

In the formula, $r^* = \arg\max_{r \in D_l} \gamma_{rd}$ denotes a relay having the best channel condition with the destination. P_s^M and P_r^M are the transmit power of the source node and the relay node for multi-relay cooperation, respectively.

3.3 Superframe structure

In this paper, the sensor node is connected to the channel by using the time division multiple access based MAC protocol to avoid data collision and reduce energy waste. Its time axis is divided into periodic superframe with length T. Superframe consists of several consecutive slots, during which a data packet from a node can be transmitted. At the beginning of each superframe, the central node allocates slots according to the channel state information and transmission rate requirement of the node, and broadcasts these information to the sensor node through beacon frames. The sensor node implements slot synchronization through the beacon frame and periodically obtains its slot allocation result, that is, adjusts the interval of the node transmission slot and the allocated number of slots, and transmits data to the central node within the allocated time.

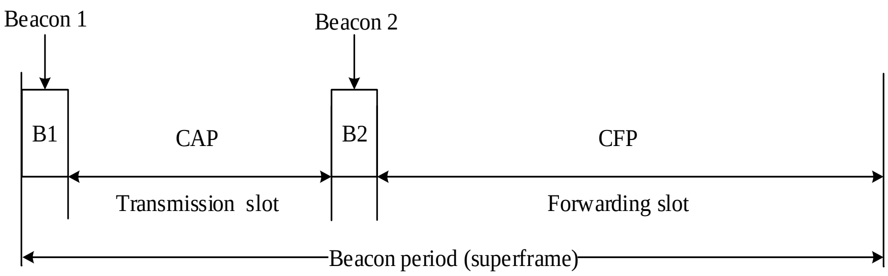

Fig. 2 Superframe structure

In order to support the proposed relay transmission strategy in the wireless body area network, a new superframe structure is proposed in this paper, as shown in Fig. 2. Each superframe can be divided into two parts: the transmission phase and the forwarding phase. On the one hand, the central node allocates the transmission slot to each sensor node in B1 according to the real-time state of the channel for data transmission; on the other hand, the central node allocates the forwarding slot to the relay node in B2 according to the historical state information of data transmission for data forwarding. Then, each sensor node transmits the collected signal to the destination node in transmission slot and forwarding slot according to the result of slot allocation of the central node to complete the reliable transmission of data.

4. SIMULATION AND PERFORMANCE EVALUATIONS

This section evaluates the performance of the proposed strategy and compares it with the QoS scheduling strategy in [10]. The scheduling approach only adjusts the transmission slot at the single hop level. In the simulated monitoring scenario, this paper uses a commonly used wireless body area network setting. Five sensor nodes are placed in different positions of the body to collect information and send it to the central node. The central node serves as the server node to coordinate Information. This is a typical setting for medical wireless body area network. According to the recommendations of the IEEE 802.15.6 working group, the transceiver at the physical layer is set to operate in the 2.4 GHz band at a transmission rate of 1024 kbps and a receiver sensitivity of -86 dBm [12]. The data rate and transmission probability requirements of the sensor nodes are set as shown in Table 1. The average noise power and SNR thresholds in the strategy are set to $N_0 = -100\,\mathrm{dB}$ and $\beta = 10\,\mathrm{dB}$, respectively. Regarding the parameter setting of the superframe structure, it is assumed herein that the superframe time slot duration is 10 ms. If not specified, the length of the superframe is set to 125ms, which is consistent with the default delay requirement for medical applications (125ms) recommended by the IEEE 802.15.6 working group [13].

Table 1 Data rate and transmission probability setting

Sensor nodes	Data rate(kbit/s)	Delivery probability threshold
Node 1	81.92	0.90
Node 2	81.92	0.90
Node 3	163.84	0.90
Node 4	163.84	0.95
Node 5	327.68	0.95

In this paper, each link is modeled as a two-state Markov chain, so P_{BG}/Q and Q can be used to describe the characteristics of the channel. where P_{BG}/Q denotes the long-term transmission probability, whose value is usually between 0.90 and 0.99. Q denotes the transition speed between two states of the channel, whose value is usually between 0.05 and 0.5 [14]. The range of the two values comes from the common data set of empirical channel measurements in wireless body area networks. The simulation runs a total of 10 times, each time randomly selecting P_{BG}/Q and Q for each node to cover a series of actual channel states. Each simulation runs 10,000 superframe periods, and the result takes the average of all 10 simulations.

In this paper, performance evaluation and comparison are carried out with reference to the improvement of transmission reliability of the proposed strategy relative to the fixed time slot allocation scheduling strategy. In order to facilitate comparative analysis, this paper introduces a relative outage probability gain, which is defined as follows,

$$\mathrm{Pout}_{reduce} = \frac{\mathrm{Pout} - \mathrm{Pout}'}{\mathrm{Pout}} \tag{18}$$

where $Pout$ is the outage probability of using the fixed time slot allocation scheduling, and $Pout^{'}$ is the outage probability of the proposed strategy. Obviously, the larger $Pout_{reduce}$, the more the outage probability drops, the better the performance of the strategy.

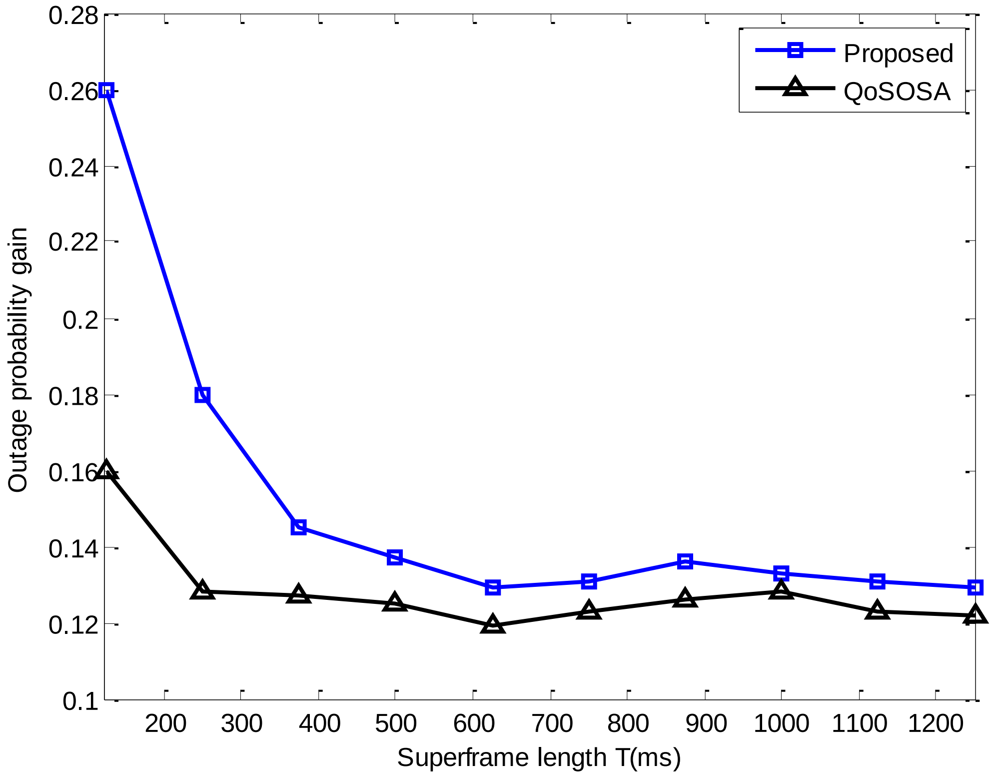

Fig. 3 Outage probability gain curve with super-frame length

Fig. 3 shows the reliability performance curves of the two strategies at different superframe lengths. It can be seen that as the superframe length increases from 125ms to 1250ms, both strategies achieve a reduction in the probability of interruption relative to the transmission strategy allocated for a fixed time slot. This is because the proposed strategy and the QoS scheduling strategy adjust the time slot based on channel state information, so that data transmission can avoid the time slot when transmission interrupts as much as possible, and improve the reliability of data transmission. The proposed strategy achieves a lower outage probability than the QoS scheduling strategy, i.e. the outage probability gain of the proposed strategy is better than that of the QoS scheduling strategy. This is because the proposed strategy not only schedules the slots according to the nature of channel fading and channel estimation in wireless body area networks, but also solves the reliability problem of data transmission at the two-hop level through the relay cooperative transmission strategy. The reliability of transmission is further improved. In addition, with the increase of superframe length, the outage probability gains of both strategies show a downward trend and then tend to be flat. The reason is that with the increase of T, the actual transmission probability tends to be the long-term transmission probability of links, so the role of channel information becomes less and less, and the transmission strategy based on channel condition estimation gains less and less.

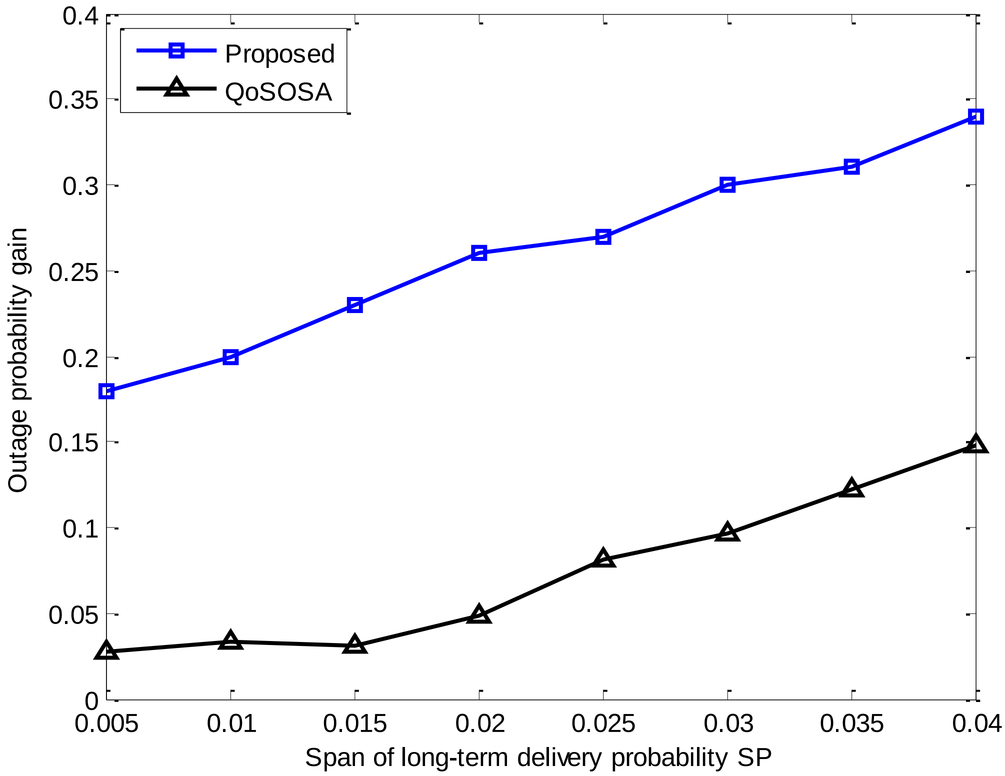

Fig. 4 Outage probability gain curve with channel SP

Then the reliability performance of the two strategies under different channel conditions is evaluated. Fig. 4 shows the curve of outage probability gain varying with SP. In this paper, the long-term transmission probability of all nodes is increased from 0.9 to 0.99, and the outage probability gain obtained by the QoS scheduling strategy is low, which indicates that a has negligible impact on the reduction of the outage probability of the strategy. Therefore, the simulation compares the reliability performance by fixing the average P_{BG}/Q of each node at 0.95 and changing the range of P_{BG}/Q (denoted by SP), i.e. randomly selecting the P_{BG}/Q value of each node from the range between $0.95-SP$ and $0.95+SP$. As shown in the figure, as the SP value of the two strategies increases, the outage probability gain increases. This is because the SP has a large range of long-term transmission probability, which means that the channel diversity of the node increases. This results in a performance degradation of the nodes in the fixed time slot allocation strategy. The outage probability gain curve of the proposed strategy is larger than that of the QoS scheduling strategy, which indicates that the strategy can better adapt to the complex wireless body area network channel characteristics, because it passes the time slot allocation and scheduling. Relay cooperation for data transmission increases the reliability of transmission at the level of double-hop communication.

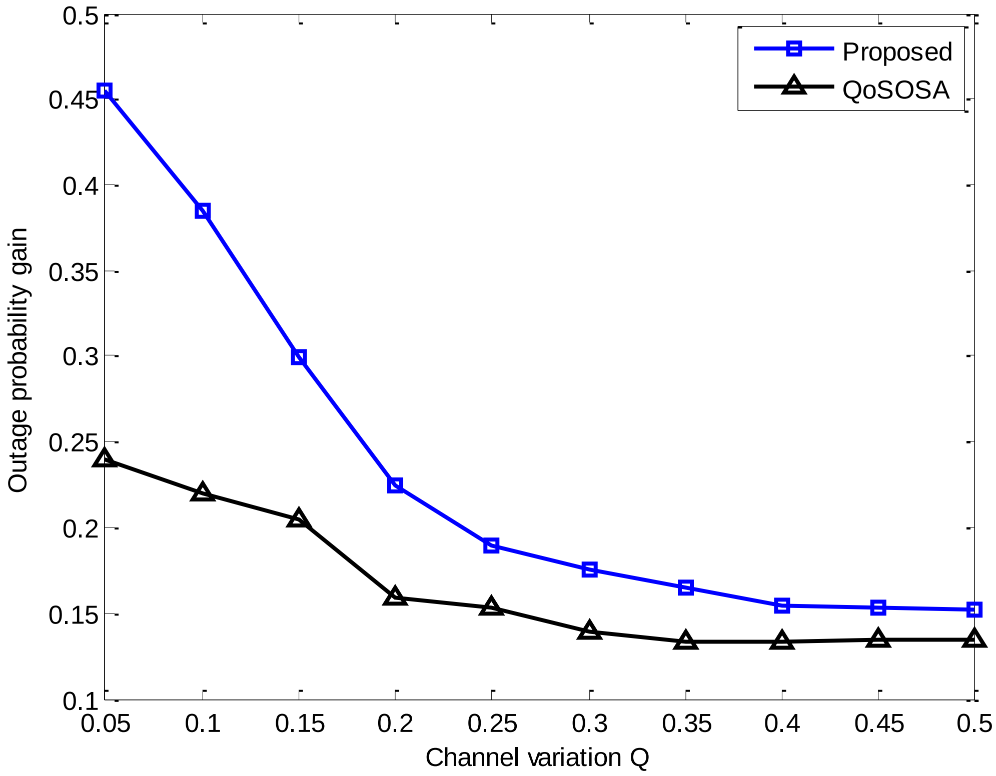

Fig. 5 Outage probability gain curve for channel change rate

Fig. 5 is a plot of the outage probability gain versus channel change rate. A series of actual values of Q (from 0.05 to 0.5) represent the rate of channel change. As can be seen from the graph, the outage probability gain of the strategy is larger when using a smaller Q, because the channel changes slowly when the Q value is smaller, and the channel condition and the nearest one in the upcoming superframe. The transmission channel conditions are more relevant, so the benefits of adjusting the time slots are more. The proposed strategy outage probability gain is higher than that of the QoS scheduling strategy. This indicates that the proposed strategy is more reliable because the strategy further improves the reliability of the transmission based on the transmission condition of the channel from the two-hop level. As the channel change speed increases, the outage probability gains of both strategies are gradually reduced. This is because when Q is large, the transmission probability of each node will approach P_{BG}/Q more quickly in the upcoming superframe. The benefits of adjusting the transmission through the channel state become less, similar to the case where the interrupt probability gain is large when the superframe length is large.

5. CONCLUSION

This paper proposes a reliable and efficient cooperative communication transmission strategy, which will introduce the dynamic time slot allocation mechanism of channel characteristics into the wireless body area network cooperative communication transmission strategy, and save energy consumption while ensuring data reliability transmission. On the one hand, the dynamic time slot allocation mechanism utilizes the reliability transmission of data and the data rate of the node as constraints, and dynamically adjusts the transmission time slot of the node according to the state information of the channel, which can improve the power consumption of the node to a certain extent. The reliability of data transmission. On the other hand, cooperative communication transmission has the advantage of spatial diversity and can provide reliable data transmission in the case of poor link conditions. The simulation results show that the strategy can adapt to complex channel conditions and node rate changes, and ensure the reliability of data transmission while balancing network energy consumption well. It has superior performance in terms of reliability and energy saving.

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