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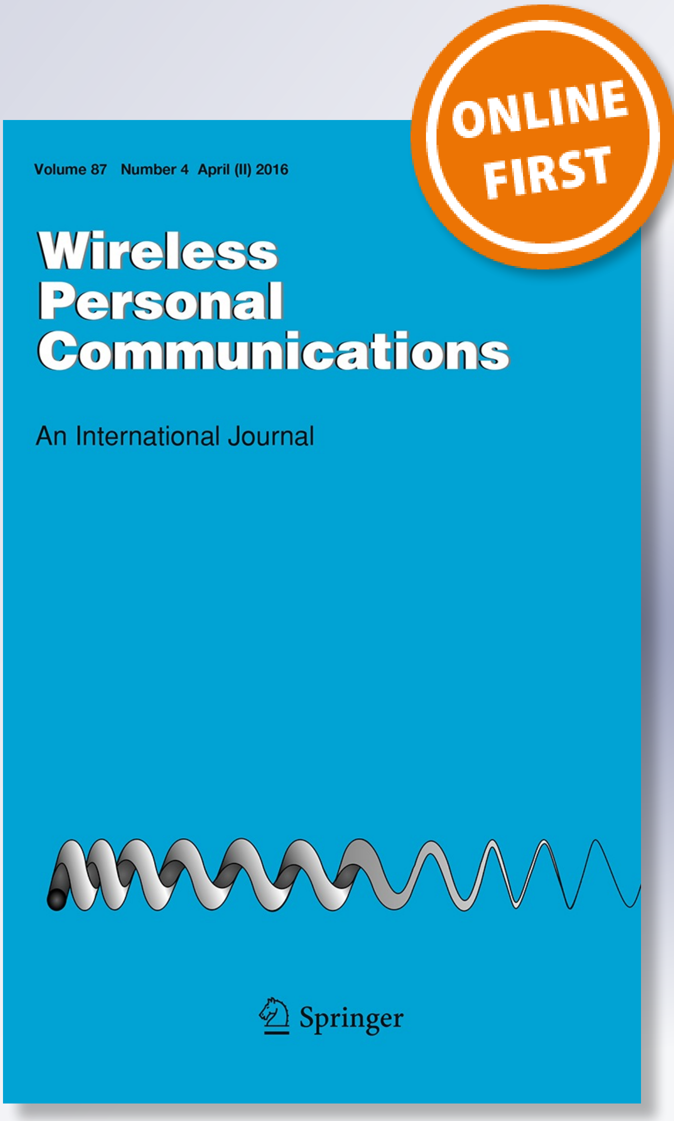

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An AHP-Based Flexible Relay Node Selection Scheme for WBANs

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Abstract A Wireless body area network (WBAN) is a communication network that provides both medical and consumer electronics services by using sensors in/on/around a human body. In general, a WBAN environment suffers from frequent link loss due to interferences among sensors scattered over a body. In addition, the channel condition can frequently change by postural body movement, which increases packet drops, retransmissions, and eventually power consumption. This paper presents an Analytical Hierarchy Process (AHP)-based flexible relay node selection scheme that considers a multitude of decision factors, such as average SNR, remaining energy ratio, and traffic load. Moreover, the proposed scheme can adaptively satisfy the requirements of WBAN in various scenarios. Our simulation study shows that the proposed method provides high communication reliability and low power consumption.

Keywords Wireless body area network · Relay node selection · AHP · Two-hop extended star topology

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1 Introduction

Rapid advances in wireless communication technologies have led to low-power, highly reliable, and miniaturized sensor nodes. This has naturally lead to a new type of network called *Wireless Body Area Networks* (WBANs) that adopt intelligent wearable sensors [1]. The IEEE 802.15 Task Group 6 (TG6) standardized WBANs in November 2007 and completed a working baseline document in February 2012. In the IEEE 802.15.6 standard, a WBAN consists of a coordinator (or a hub), sensor devices, and consumer electronic (CE) devices that function in, on, or around the human body to provide medical and CE services [2].

The two major requirements of WBAN are as follows: First, a WBAN has to provide reliable communication because medical services are directly related to the safety of human lives. However, network conditions frequently change due to the variability of WBAN environments. For example, sensor nodes in a WBAN exhibit mobility due to postural body movement, which can cause link loss between the coordinator and sensor nodes. Frequent link losses decrease network stability and lead to network partitioning. In addition, in-body sensor nodes communicate through the human body medium, which has different characteristics than the air medium, such as higher signal attenuation and link loss.

Second, sensor nodes in a WBAN need to operate using battery power in order to provide mobility. Due to this requirement, low power consumption for WBAN devices is one of the most important research issues. In particular, it is difficult to replace or recharge batteries of in-body sensors. To satisfy this requirement, technical requirement document (TRD) published by the IEEE 802.15.6 defines low duty cycle (i.e., sampling rate) to reduce the average transmission power consumption [3].

The aforementioned variabilities in WBANs increase packet drop rate, retransmission rate, and power consumption. In addition, the communication power of each device, which increases as a function of distance between nodes, is typically higher than the processing power. Therefore, using relay nodes in WBANs is an efficient way to reduce power consumption.

To tackle these issues, the IEEE 802.15 TG6 defines a two-hop star topology extension to help establish a new link [4]. This is illustrated in Fig. 1, where a node (e.g., Node 4, 5, or 6) and the coordinator can use a two-hop communication to exchange frames through another node referred as a *relay node* (i.e., Node 1 or 2). In order to establish a relayed communication, either the coordinator or the node initiates the two-hop communication by sending a control message. The relay node also directly sends its own frames to the coordinator just as in a one-hop star network. However, the two-hop star topology extension of IEEE 802.15.6 does not specify how a relay node should be selected. The standard also does not consider a variety of requirements for different service applications and network conditions that change frequently.

Recently, numerous studies have focused on how to select relay nodes in ad-hoc networks, cooperative communications, cognitive radios, and wireless sensor networks (WSNs) [5–14]. Most of these studies, however, assume that nodes are deployed in a large-scale geographical region, and they support more than two-hop transmissions. Furthermore, these studies assume each node has abundant resources, such as GPS, battery, and computation power, which allow for more complex schemes to be applied to solve the aforementioned problems. In contrast, a WBAN does not support more than two-hop transmission because nodes are deployed within a short range of at most 3 m with small

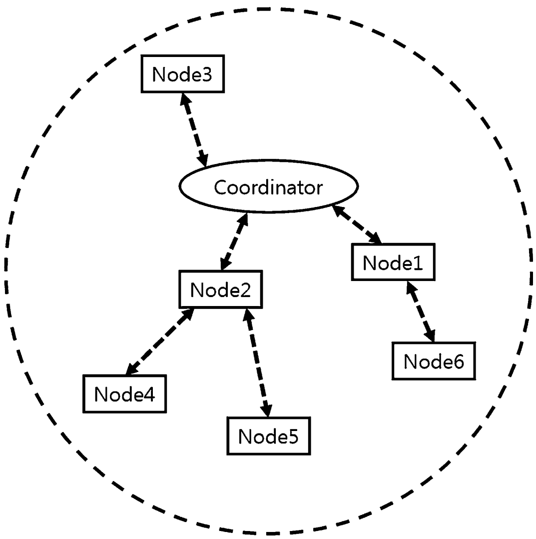

Fig. 1 The *two-hop star* topology defined in the IEEE 802.15.6 standard

battery capacity, and the communication range of each node can cover all the other nodes in the network.

There are some existing work with the purpose of increasing network lifetime of WBANs using relay nodes [15–17]. However, these studies assume fixed network topologies, and thus, dynamic network changes caused by postural body movements are not taken into account. In addition, since they assume multi-hop transmission (usually more than two hops), these methods are not compliant with the two-hop extension of the IEEE 802.15.6 standard. The authors in [18] modified the two-hop star topology extension of IEEE 802.15.6 to reduce the number of exchanged messages and to prolong network lifetime. This scheme assumes that the coordinator is capable of transmitting data directly to all of the nodes in the network without involving intermediate relay nodes. However, the wireless link between the coordinator and sensor nodes can be disconnected due to the characteristics of human body medium and postural body movements regardless of the transmission power of the coordinator or the sensitivity of receiver nodes. Moreover, their work does not try to find the optimal relay node.

In order to overcome the shortcomings of the existing methods, this paper proposes an *analytical hierarchy process (AHP) based flexible relay node selection scheme* for WBANs. The specific contributions of this paper are as follows:

– To overcome the problem of frequently and dynamically changing network conditions, the proposed method applies AHP to provide a *flexible* decision making process for relay node selection by considering various factors, such as high reliability and low power consumption.
– Unlike existing relay node selection schemes, the proposed scheme is compatible with the two-hop star topology extension of IEEE 802.15.6.
– The performance of the proposed scheme is compared with the IEEE 802.15.6 standard in terms of packet reception ratio (PRR), power consumption, delay, and network life time. Our simulation results show that the proposed scheme outperforms IEEE

802.15.6 and can be flexibly applied to various applications of WBAN with different requirements and scenarios.

The rest of the paper is organized as follows: Sects. 2 and 3 present the two-hop star topology extension in IEEE 802.15.6 and discusses the existing work on relay node selection. Section 4 presents the proposed scheme that consists of relay candidates discovery, AHP-based relay node decision, and direct link recovery. Section 5 discusses our simulation results and Sect. 6 concludes the paper.

2 Background: Two-hop Star Topology Extension of IEEE 802.15.6

This section discusses the two-hop star topology extension of IEEE 802.15.6 to help readers better understand the motivation for the proposed scheme. Figure 2 shows the relay discovery and selection procedure in the two-hop star topology extension, which can be either coordinator centric or relay node centric [4].

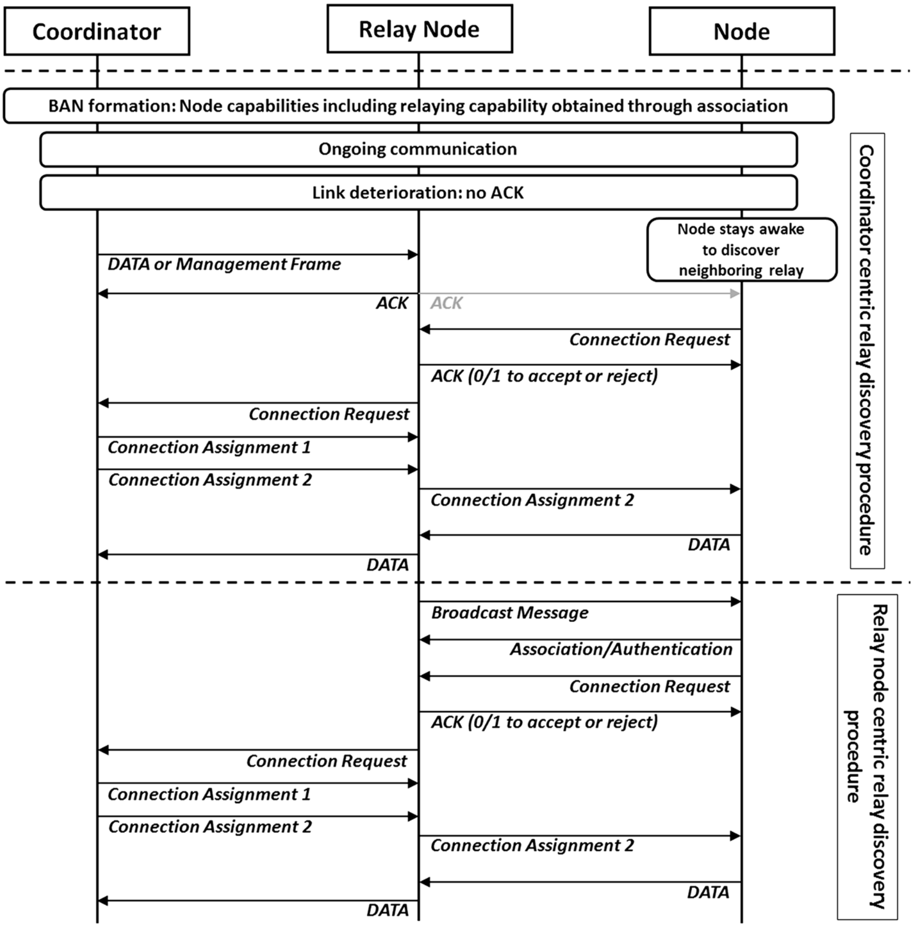

Fig. 2 The relay discovery and selection procedure for the *two-hop star* topology extension of IEEE 802.15.6

In the *coordinator centric* approach, the node initiates a procedure to find and establish a link to a relay node when it detects that the communication link with the coordinator is poor. This is achieved by overhearing *ACK* or *Management* frames originating from a relay node and destined to the coordinator, which indicates that the relay node is within the range of both the coordinator and the node and the link between the relay node and the coordinator is reliable. The node will then initiate the establishment of a new link with the discovered relay node by sending a *Connection Request* message to the relay node. If the relay node accepts the request, it forwards this message to the coordinator and sends an *ACK* to the node. When the coordinator receives the *Connection Request* message from the node, it sends a *Connection Assignment 1* message to inform the relay node of the updated radio resource allocation between the coordinator and the relay node. The coordinator also sends a *Connection assignment 2* message to inform the relay node of the additional radio resource allocation for the new link between the relay node and the node, which is then forwarded to the node. Finally, the node can send data to the coordinator through the relay node.

Figure 2 also illustrates the relay discovery procedure for the *relay node centric* approach. This approach provides the new relay link establishment to both connected and disconnected nodes. A relay node may optionally provide synchronization to the nodes in the WBAN (connected or disconnected) when it operates based on the Beacon-enable mode. This is done by having the relay node send a *Broadcast* message, which includes a timestamp and resource allocation specification. The purpose of the *Broadcast* message is to provide the disconnected nodes an opportunity to establish a connection with a suitable relay node in order to communicate with the coordinator. After the node receives the *Broadcast* message, it will authenticate the relay node. If the authentication is successful, the node transmits *Connection Request* message to the relay node to request for additional resources for communication between the relay node and the node. The next resource allocation procedure for the relay node centric approach is the same to as the coordinator centric approach.

Note that in both coordinator and relay node centric approaches, the node selects the first relay node that replies with an *ACK*. This means that the IEEE 802.15.6 standard does not consider multiple relay candidates to provide adaptiveness to continuously changing network condition, network lifetime, and latency. Moreover, IEEE 802.15.6 does not provide any provisioning to recover the direct link between the coordinator and the node when the network condition improves, which can eliminate the unnecessary power consumption of the relay node.

3 Related Work

A number of studies exist on relay node selection and routing schemes for ad-hoc networks [5–7]. Yaozhou et al. [5] proposed a flexible relay node selection scheme and a routing protocol based on analytical hierarchy process–Gray relational analysis (AHP–GRA), which considers the number of message copies over the network, the expected path length, and the priority of messages. They assumed that the network requires only communication reliability in a mobile environment without consideration of latency and energy consumption, and this assumption is similar to ones used in the delay tolerant network (DTN) scenario. Adaptive rate-and-relay selection with Greedy perimeter stateless routing (GPSR) was considered in [6], where a throughput product metric function is determined based on node location and SNR to improve network throughput. To provide adaptability to the IEEE 802.11 standard, the authors developed a scheme based on distributed coordination function (DCF). Kim et al. [7] proposed an opportunistic network coding (OPNC) with relay node selection for wireless communications. They consider a system model that includes multiple relay nodes and multiple sink nodes. Based on the system model, they propose a relay selection scheme which considers the channel state between relays and destination nodes, and they combine the proposed relay selection model with network coding to improve average system throughput. These schemes focused on improving network performance, but energy efficiency was not considered. Moreover, they assumed that nodes are deployed in a large-scale area and can transmit data to the destination using more than two-hops, which is not supported in WBANs. Consequently, these schemes cannot be directly applied to WBANs.

Relay node selection is an important issue in both cooperative communication and cognitive radio research communities [8–12]. Tao et al. [8] employed the optimal stopping theory to take into account the time required to scan for candidate relay nodes before stopping at a suitable one with good channel quality in a cognitive radio environment. Their scheme guarantees that such a relay node will be found within a short observation/scan time. Krikidis et al. [9] investigated a relay selection scheme for a finite buffer-aided decode-and-forward cooperative wireless network. In order to maximize the achieved diversity gain, the proposed scheme fully exploits the buffering capability at relays and provides transmission scheduling for available channel links. To evaluate performance of the proposed scheme, the authors perform extensive simulations and verify the performance of the proposed scheme in terms of outage probability and diversity gain by providing a significant coding gain for small buffer size. Zhang et al. [10] proposed a low overhead multi-relay selection protocol to support multi-stream cooperative communications for multi-stream cooperative multiple input multiple output (MIMO) systems with multiple relay nodes. At high signal-to-noise ratio (SNR) value, the proposed protocol obtains good trade-offs between diversity and multiplexing or throughput and reliability when using lower outage probability value. Song et al. [11] considered a simple suboptimal min-max criterion for relay selection, called 'Relay Selection Amplify-and-Forward (RS-AF)', which selects a single relay that minimizes the maximum symbol error rate between two sources. To improve the system performance, the authors determine the optimal power allocation (OPA) between the sources and the relay based on asymptotic symbol error rate. Theoretical analysis and simulation indicate that their RS-AF with OPA achieves the full diversity for multiple relays scenario. Elrabiei et al. [12] proposed an energy-efficient cooperative multicasting scheme that selects relay nodes based on their location, channel condition, and coverage. They considered worldwide interoperability for microwave access (WiMAX) single frequency networks, and simulated a nearest neighbor protocol and transmission radius relay agent (RA) selection algorithm, including two further optimized versions of them based on the transmission range of relay node and the instantaneous channel state information. These schemes assumed a mobile environment and a relay infrastructure that have plentiful resources. Moreover, most of these studies focused only on improving performance of relaying transmissions in terms of latency and throughput, but did not consider both transmission reliability and power consumption. In contrast, a WBAN consists of nodes that have limited resources and requires low overhead and low power consumption on relay nodes.

In general, nodes in WSNs have limited resources. To overcome this problem, there are a number solutions on relay node selection and routing protocol for WSNs. Tuah et al. [13] proposed a relay node selection scheme to minimize power consumption and extend network lifetime in cluster-based WSNs with heterogeneous sensor nodes. They assumed that the placement of relay nodes in the network is important when each node has different capacity. To achieve energy efficiency, the authors proposed a three layered architecture and two algorithms called highest energy levels relay selection' and minimum energy over distance rate relay selection. These algorithms first select cluster heads and then select a relay node from the selected cluster heads. de Graaf [14] introduced an analytical model to maximize network lifetime for various clustering algorithms, which is related to the research on hierarchical routing protocols for wireless sensor network. The author constructs a general power consumption model and performs numerical analysis for two different cases (fixed and uniformly distributed power case, and geometrical power case). However, due to the different requirements of a WBAN, such as rapid channel variation due to postural body movement, more constrained energy consumption requirement, and small-scale high-density network, existing schemes for WSNs cannot satisfy the requirements of WBANs.

A number studies have been done to extend the network lifetime of WBANs using relay nodes [15–18]. Ehyaie et al. [15] proposed a method that employs optimal power allocation with the constraint of targeted outage probability to minimize energy consumption. The method considers two strategies—power allocation with and without posture state information. An on-body packet routing algorithm for WBAN was considered in citeref2. To avoid packet loss due to frequent postural network partitioning, the authors presented relative location based forwarding (RLOCF), where network partitioning pattern was measured and analyzed based on experiments. Elias et al. [17] investigated the effect of adding a relay network to the network of body sensors to reduce energy consumption. The authors defined a relay node that only has relaying capacity without sensing capacity. In their method, when the network is initialized, a network topology is constructed based on the predetermined number of relay nodes and their locations. However, their study only focused on the initial locations of nodes and does not take into account frequent link loss due to human activity and postural movement. In an another perspective, a WBAN standard-based energy efficient two-hop star topology extension was proposed in [18]. This scheme assumes that the coordinator is capable of transmitting data directly to all of the sensor nodes without relay nodes, which will increase power consumption and the cost of nodes. Moreover, they did not consider how to efficiently select relay nodes.

As mention above, existing relay node selection and routing schemes cannot be directly apply to WBANs due to different communication environment and requirements. Therefore, a relay node selection scheme that satisfies the requirements and characteristics of WBAN is necessary. To provide reliable communication with low delay, a relay node selection method for WBANs should consider various factors for different scenarios, such as dynamic link losses due to intra-network mobility.

4 A Flexible Relay Node Selection Scheme for WBANs

Our proposed method focuses on adaptively satisfying the requirements of WBANs to prolong the network lifetime and improve reliability in situations where signal attenuation and link loss occur frequently due to dynamic node mobility.

Figure 3 illustrates the proposed AHP-based Flexible Relay Node Selection scheme. First, when a node looses its direct link to the coordinator, the discovery of relay candidates is initiated by a simple control message exchange. Second, among the available relay

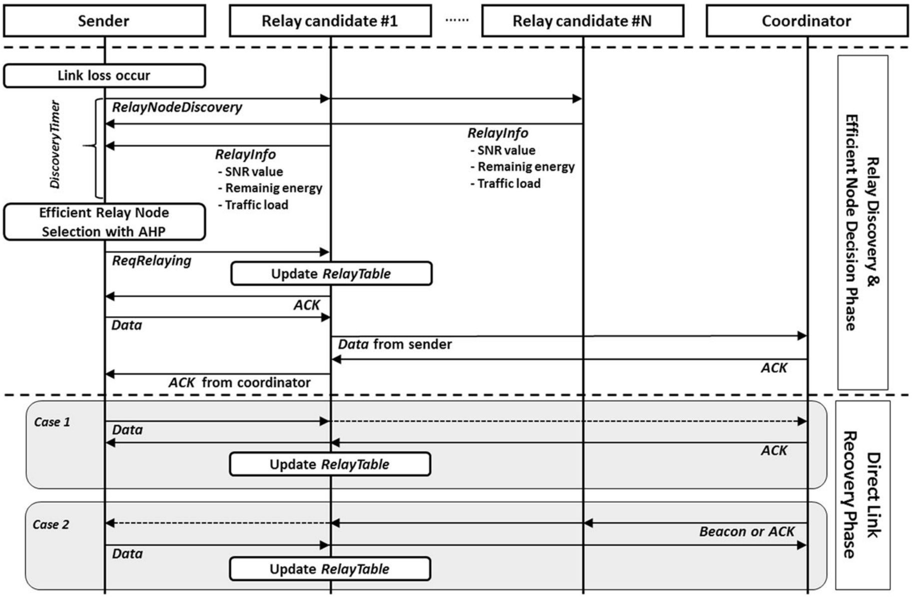

Fig. 3 Overall sequence of the proposed scheme

candidates, the node decides on a relay node using AHP and establishes a relay link with the selected relay node. Finally, the recovery of the direct link between the coordinator and the node, if possible, is carried out.

The proposed method is implemented using the following three modules: *Relay Candidates Discovery*, *AHP-based Relay Node Decision*, and *Direct Link Recovery*. The following subsections provide detailed discussions of the three modules.

4.1 Relay Candidates Discovery

Relay Candidates Discovery is performed using a control message called *RelayNodeDiscovery*. If the node does not receive a *BEACON* or an *ACK* message, it broadcasts a *RelayNodeDiscovery* message to neighboring nodes and sets the *DiscoveryTimer*. Our scheme only selects on/around-body devices as relay nodes. This is because in-body medical devices have small battery capacity and their replacement requires surgery, and thus it is impractical to use these devices as relay nodes.

When the relay candidates receive the *RelayNodeDiscovery* message, each relay candidate i sends a *RelayInfo* message, which contains average SNR value, total traffic load, and remaining energy ratio.

Average SNR for node i, $AvgSNR_i$, represents SNRs of the coordinator and the node relative to a relay candidate, and is given as

$$AvgSNR_i = \frac{SNR_{i\to cord} + SNR_{i\to node}}{SNR_{i\to cord} \times SNR_{i\to node}}, \tag{1}$$

where $SNR_{i\to cord}$ is the SNR from the coordinator to the relay candidate i and $SNR_{i\to node}$ is the SNR from the relay candidate i to the node.

The total traffic load of the relay candidate i, TL_i^{total}, is defined as

$$TL_i^{total} = \frac{1}{TL_i + \sum TL_{RelayingNode}}, \tag{2}$$

where TL_i denotes the relay candidate i's own traffic and $TL_{RelayingNode}$ denotes traffic load of the other nodes that communicate with the coordinator via relay candidate i.

The remaining energy ratio of node i, E_i^{Ratio}, is defined by the following equation:

$$E_i^{Ratio} = \frac{E_i^{Rest}}{E_i^{Init}}, \tag{3}$$

where E_i^{Rest} and E_i^{Init} represent the residual and initial energy of node i, respectively.

When the *DiscoveryTimer* expires, the node constructs a table of relay candidates based on received *RelayInfo* messages, and then selects a relay node using the AHP-based relay node decision model that will be explained in the next subsection.

4.2 AHP-Based Relay Node Decision

The AHP is a multiple criteria decision-making method that decomposes a complex problem into a hierarchy of simpler and more manageable sub-problems [19]. These sub-problems are referred to as *decision factors* or *criteria*, and each factor is given a *weight* according to its relative importance to the problem. Consequently, the importance of each factor to the problem is synthesized to find the best solution.

Our proposed method uses AHP to determine the weights of the relay candidates according to which next hop is selected when a relay link is established. Figure 4 shows the AHP hierarchy model for the relay node selection. In the model, the goal of the decision "Efficient selection of relay node" is at the top of the hierarchy. The average SNR, traffic load of the relay candidate, and remaining energy ratio are taken into consideration as the decision factors, which are in the middle level of the hierarchy model. The bottom level consists of m alternative relay candidates to be evaluated. Based on the pre-constructed AHP hierarchy model, the *weight acquiring process* is carried out using the following three steps:

1. Collect information and formulate the relay node selection problem as a decision hierarchy of independent factors.

Fig. 4 AHP hierarchy for relay node selection

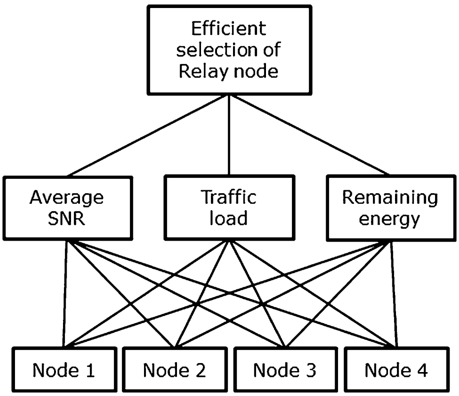

Table 1 A fundamental 1 to 9 scale

Number rating	Verbal judgment of preferences
1	Equally preferred
3	Moderately preferred
5	Strongly preferred
7	Very strongly preferred
9	Extremely preferred

2. Decide and calculate the relative local weights of decision factors or alternatives of each level.
3. Synthesize the above results to determine the overall weight of each alternative nodes and choose the one with the largest weights as the appropriate relay node.

The local weights consist of two parts: the weight of each decision factor to the goal and the weight of each candidate to each decision factor. Both are calculated using the same procedure. Taking the former as an example, the following describes the procedure.

An evaluation matrix is developed using a pairwise comparison of each decision factor under the topmost goal. The comparison results are generated by asking questions, such as "Which is more important and by how much?", and are presented as a square matrix A given by

$$\mathbf{A} = (a_{ij})_{n\times n} = \begin{pmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{pmatrix}, \tag{4}$$

where a_{ij} denotes the ratio of the ith weight factor to the jth weight factor, and n is the number of factors. Each weight factor is decided by the user or the service provider based on the fundamental 1 to 9 scale, which can be used to rank the judgments as shown in Table 1. The smaller weight in a pair is chosen as a unit and the larger weight is estimated as a multiple of that unit, and then a number is assigned based on the perceived importance. Similarly, the reciprocals of these numbers can also be used to show the inverted comparison results. Thus, a reciprocal matrix can be obtained where the entries are symmetric with respect to the diagonal.

For the matrix A, its eigenvalue is calculated based on the equation $AW = \lambda_{max}W$, where W is a non-zero vector called eigenvector, and λ_{max} is a scalar value called eigenvalue. After standardizing the eigenvector W, the elements of W are regarded as the approximate local weights of the decision factors expressed as

$$W_j^T = \{w_\alpha, w_\beta, w_\gamma\}, \tag{5}$$

where w_α, w_β, and w_γ are approximate local weights for the average SNR, traffic load of the relay candidate, and remaining energy ratio, respectively.

If every element in Eq. (4) satisfies the equations $a_{ij} + a_{ji} = 1$ and $a_{ik} + a_{kj} = a_{ij}$, the matrix A becomes a consistency matrix. Unfortunately, the evaluation matrices are often not perfectly consistent due to people's random judgments. These judgment errors can be detected by a consistency ratio (CR), which is defined as the ratio of consistency index (CI) to random index (RI) as shown below.

$$CR = CI/RI, \tag{6}$$

where RI is given in Table 2 [19], and CI is defined as

Table 2 Consistency index

n	1.2	3	4	5	6	7	8	...
RI	0	0.58	0.9	1.12	1.24	1.32	1.41	...

$$CI = (\lambda_{max} - n)/(n - 1), \tag{7}$$

where

$$\lambda_{max} = (1/n)\sum_{i=1}^{n}(AW)_i/W_i. \tag{8}$$

When $CR \leq 0.1$, the judgment errors are considered to be tolerable, and the weight coefficients of the global weight W_j becomes the weights of decision factors under the topmost goal. Otherwise, pairwise comparisons need to be adjusted until matrix A satisfies the consistency check.

From the above steps, not only the weights of decision factor from W_j towards the topmost goal can be obtained, but also the weights of the candidate nodes towards each factor. As an example, suppose a node has four neighbors in a WBAN. Then, the weights of four alternatives under the three factors result in a 3×4 matrix, denoted as w_{n_ij}, shown below.

$$w_{n_ij} = \begin{array}{c} \\ \\ n_1 \\ n_2 \\ n_3 \\ n_4 \end{array} \begin{array}{c} \begin{array}{ccc} Average & Traffic & Remaining \\ SNR & Load & Energy \end{array} \\ \begin{pmatrix} w_{11} & w_{12} & w_{13} \\ w_{21} & w_{22} & w_{23} \\ w_{31} & w_{32} & w_{33} \\ w_{41} & w_{42} & w_{43} \end{pmatrix} \end{array} \tag{9}$$

where n_1, n_2, n_3, and n_4 denote the candidate relay nodes.

The global weight of each sensor node can be derived by multiplying the local weight to its corresponding parent. As a result, the final weight matrix w_{n_i} is calculated as

$$w_{n_i} = w_{n_ij} \cdot w_j, \tag{10}$$

where each alternative neighbor's final weight is calculated as

$$w_{n_i} = \sum_{j=1}^{3} w_{n_ij} \cdot w_j. \tag{11}$$

The larger the final weight of the neighbor node, the higher the importance it has towards enhancing the performance of network lifetime or reliability. Thus, the neighbor with the largest weight is selected as the relay node.

The following example illustrates the AHP process, where the matrix A is determined according to Eq. (4) and shown below:

$$
\mathbf{A} = \begin{array}{c c}
 & \begin{array}{ccc} Average & Traffic & Remaining \\ SNR(\alpha) & Load(\beta) & Energy(\gamma) \end{array} \\
\begin{array}{c} \alpha \\ \beta \\ \gamma \end{array} & \left(\begin{array}{ccc} 1 & 1/2 & 1/4 \\ 2 & 1 & 1/2 \\ 4 & 2 & 1 \end{array} \right)
\end{array} \tag{12}
$$

where the three criteria are denoted by α, β, and γ.

In this example, the service provider regards energy consumption as the most significant criterion, traffic load as the second important criterion, and the average SNR as the third important criterion, and their overall relative importance $\alpha:\beta:\gamma$ is given as 4:2:1. Therefore, relative importances of the three possible pairs of criteria $\alpha:\beta$, $\beta:\gamma$, and $\gamma:\alpha$ are 1:2, 1:2, and 4:1. Based on this assumption, the eigenvector can be calculated as $W = \{0.142857, 0.285714, 0.571429\}$, which indicates the local weights of the average SNR, traffic load, and remaining energy, respectively. Based on this, it is clear that the remaining energy is the most important criterion, and the average SNR is the least important. According to Eq. (8), the eigenvalue is $\lambda_{max} = 3.0$. Consequently, consistency ratio can be calculated as $CR = 0.0 < 0.1$, thus matrix A satisfies the consistency check.

Information of each relay candidate determines the weight matrixes of alternatives under the three factors, and then global weight is obtained based on its specific situation. Finally, its eligibility as a relay node can be decided by the AHP hierarchy model.

Afterwards, the node sends a *ReqRelaying* message to the selected relay node, and the relay node inserts the node's information into its *RelayTable*. Then, the relay node can pass on *BEACON*, *DATA*, and *ACK* message between the coordinator and the node.

4.3 Direct Link Recovery

Since the network conditions continuously change, the disconnected link between the coordinator and the node may be recovered. If no attempt is made to recover the direct link even when it is possible, the relay node will consume unnecessary energy and transmission latency will increase. For this reason, the Direct Link Recovery algorithm is proposed.

Figure 5 shows the details of the direct link recovery algorithm. The first case represents the direct link recovery process from the perspective of the coordinator. If the coordinator overhears a *DATA* frame from the node to the relay node, it designates the node as the destination for an *ACK* frame. After the node receives the *ACK* frame, it checks the information in the received frame and directly communicates to the coordinator. The second case represents the direct link recovery process from the perspective of the node. If the node can overhear a *BEACON* or an *ACK* frame from the coordinator, then the node recovers the direct link to the coordinator. Meanwhile, the relay node releases the node's information in the *RelayTable* when it overhears a *BEACON*, an *ACK*, or a *DATA* frame.

5 Performance Evaluation

This section discusses the performance evaluation of our scheme through simulation using various scenarios. As mentioned in Sect. 3, network environments of existing relay node selection schemes and routing protocols for ad-hoc, cooperative communication, cognitive

```
PROCEDURE OF Direct LINK RECOVERY
When COORDINATOR attempts Direct Link Recovery:
    COORDINATOR:
    if((RcvPkt→DestAddr != COORDINATOR) && RcvPkt→type == DATA)) {
            set DestAddr to Rcv→SrcAddr
            send ACK message
    }

    NODE:
    if((RcvPkt→DestAddr == this→Addr)
        && (RcvPkt→type == ACK) && (this→useRN == TRUE)) {
            set DestAddr to COORDINATOR
    }

When NODE attempts Direct Link Recovery:
    NODE:
    if((RcvPkt→DestAddr == this→RNAddr) &&
        (RcvPkt→isRN == TRUE) && (RcvPkt→type == BEACON || ACK)) {
            set DestAddr to COORDINATOR
            if(isEmpty(this→queue) == FALSE) {
                    send DATA
            }
    }

Operation of RELAY NODE
after COORDINATOR or NODE performs Direct Link Recovery:
    cnt = 0
    if(RcvPkt→isRN == FALSE) {
            while(cnt != RelayTableLength) {
                    if(RcvPkt→SrcAddr == RelayTable[cnt]→Addr) {
                            release(RelayTable[cnt])
                            break
                    }
                    cnt++
            }
    }
```

Fig. 5 Pseudo-code algorithm for direct link recovery

radio, and WSN [5–14] are different from WBAN. Moreover, requirements of WBAN is more strict than existing works. Therefore, they are not suitable to be directly applied to WBAN environment. In addition, relay selection schemes for WBAN [15–18] also cannot be considered as subjects of a comparison for the simulation due to their strong assumptions. By these reasons, we compared with the two-hop star topology extension scheme in the IEEE 802.15.6 standard. The proposed method is implemented with OMNeT++ [20].

5.1 Simulation Model

In our simulation, sensor nodes are randomly deployed in a circular area with a radius of 3 m. The coordinator is placed at the center of the network, and the number of sensor nodes is 20. The transmission range of the sensor nodes is 3 m and each has 1 mJ as the initial energy. The default network is a one-hop star topology and the sensor nodes periodically generate 240 bytes of data. Link loss occurs uniformly on every link in the network with a percentage. The PHY layers of the proposed method and the IEEE 802.15.6 standard are identical to those of IEEE 802.15.4 [21], and each link state is decided based on randomly changing SNR values based on the percentage of link loss. The energy consumption model of LEACH [22] is used to simulate energy consumption of the sensor nodes. The *DiscoveryTimer* for the Relay candidates discovery module of the proposed method is set to 1 ms, and the maximum retransmission count is 3.

5.2 Simulation Scenarios

To evaluate the flexibility and adaptability of the proposed scheme, the following four scenarios that reflect various real situations in WBANs are defined: *Normal Medical Service*, *Low Battery*, *Critical Medical Service*, and *Emergency*. In these scenarios, the average SNR, remaining energy ratio, and traffic load of the relay candidates are set as the first, second, and third weight factors, respectively, for the following priority matrixes. Details of these scenarios are discussed below.

Scenario 1—Normal medical service This scenario assumes that a WBAN consists of typical medical devices, which have enough energy capacity and the same priority for frames. In this scenario, there are no exceptional situations such as emergency, low battery, etc., and thus, the relative weights of all the criteria is the same and the priority matrix A_{Normal} is set as shown below:

$$\mathbf{A}_{\mathbf{Normal}} = \begin{pmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix} \tag{13}$$

Scenario 2—Low battery This scenario assumes that the remaining energy in the network is low. Therefore, low power consumption is more important than Scenario 1, and the relative weight for the remaining energy should be higher than other criteria. Thus, the priority matrix $A_{LowEnergy}$ is set as follows:

$$\mathbf{A}_{\mathbf{LowEnergy}} = \begin{pmatrix} 1 & 1 & 1/5 \\ 1 & 1 & 1/5 \\ 5 & 5 & 1 \end{pmatrix} \tag{14}$$

Scenario 3—critical medical service This scenario considers some medical devices that are critical to a user's health, referred to as *Critical Medical Devices*, and require reliable communication. Therefore, this scenario rates the communication reliability as a top priority, and the priority matrix $A_{Critical}$ is defined to guarantee high reliability of critical medical data. The priority matrix $A_{Critical}$ is expressed as follows:

$$\mathbf{A_{Critical}} = \begin{pmatrix} 1 & 5 & 5 \\ 1/5 & 1 & 1 \\ 1/5 & 1 & 1 \end{pmatrix} \tag{15}$$

Scenario 4—emergency In this scenario, a WBAN must be able to guarantee prompt and reliable transmission during an emergency situation. A WBAN should immediately handle situations when devices sense irregular data during monitoring of vital signals. Otherwise, user's critical requests may not be delivered. Based on this, the priority matrix $A_{Emergency}$ shown below reflects the importance of link quality and traffic load:

$$\mathbf{A_{Emergency}} = \begin{pmatrix} 1 & 1 & 5 \\ 1 & 1 & 5 \\ 1/5 & 1/5 & 1 \end{pmatrix} \tag{16}$$

5.3 Simulation Results

Figure 6 compares the PRR values of the proposed scheme and IEEE 802.15.6 as a function of the percentage of link loss for the four scenarios. In general, Scenarios 3 and 4 outperform other scenarios since their priority matrices reflect the fact that reliability is more important than energy consumption. On the other hand, Scenario 2 shows the lowest PRR for the proposed scheme. However, since the proposed scheme reflects both average SNR and traffic load into the selection of relay nodes using AHP for all the scenarios, it can provide PRR of up to 90 % until the percentage of link loss falls below 60 %. In contrast, PRR of IEEE 802.15.6 decreases linearly as the percentage of link loss increases, which is due to the fact that link states are not considered in IEEE 802.15.6.

Figure 7 shows the average power consumption of the proposed scheme and IEEE 802.15.6 for Scenario 1 as a function of the percentage of link loss. The average power

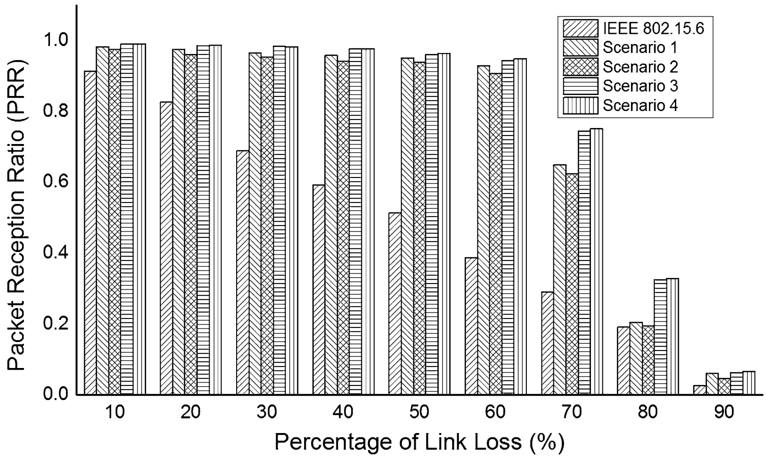

Fig. 6 Packet Reception Ratio (PRR) versus percentage of link loss

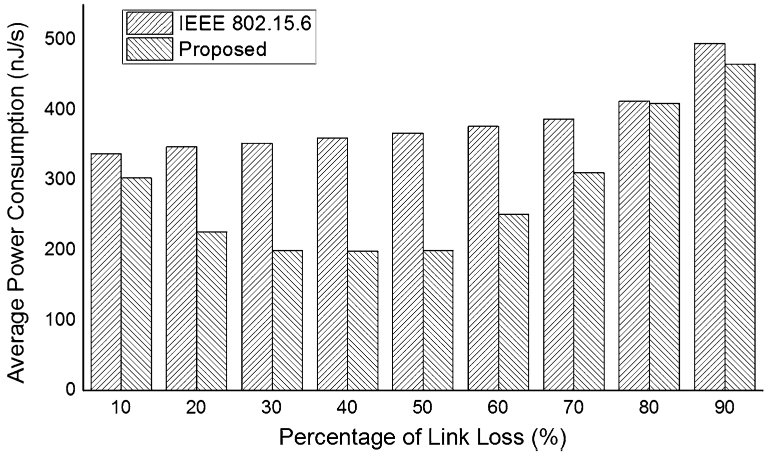

Fig. 7 Average power consumption versus percentage of link loss

consumption for the proposed scheme decreases until the link loss reaches 40 %, but increases afterwards. The decrease in the first half occurs because the proposed scheme dynamically selects relay nodes when link losses occur, and this leads to reduction in the number of retransmissions. In addition, the number of additional control messages exchanged decreases as the link loss ratio increases because the number of available links decreases. Based on this, the average power consumption of the proposed scheme decreases when link loss increases. However, the average power consumption of the proposed scheme drastically increases when link loss is >40 %. This can be explained by the fact that the number of retransmissions rapidly increases in situations where link loss is frequent. On the other hand, the average power consumption of IEEE 802.15.6 increases linearly as the percentage of link loss increases, and it is always higher than the proposed

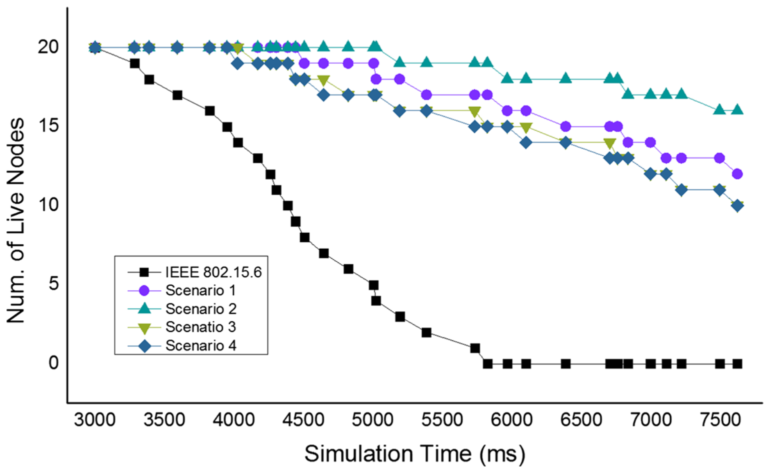

Fig. 8 Number of live nodes versus time

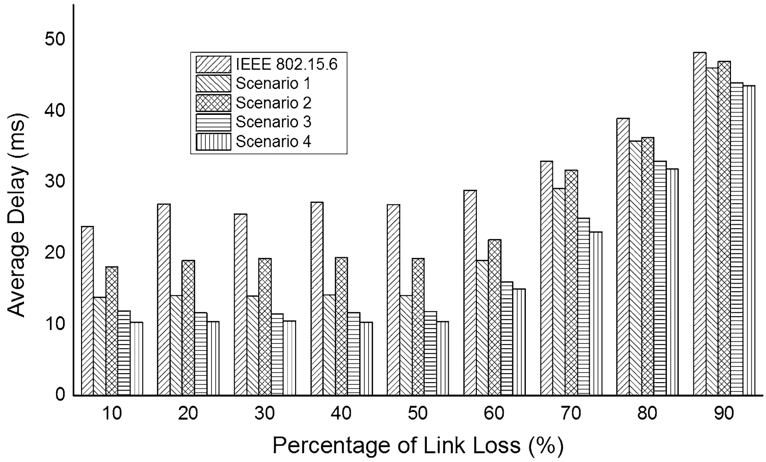

Fig. 9 Average delay versus percentage of link loss

scheme. This indicates that proposed scheme can achieve better energy efficiency than IEEE 802.15.6 despite the overhead due to control message exchanges.

Figure 8 tracks the number of live nodes as simulation progresses when the percentage of link loss is 40 %. The number of retransmissions for IEEE 802.15.6 is larger than the proposed scheme since it cannot dynamically handle link loss among the coordinator, relay nodes, and nodes. Therefore, the proposed scheme maintains a higher survivable rate of nodes by considering the remaining energy. In particular, the results of Scenario 2 show the longest network life time since remaining energy has a higher weight than average SNR or traffic load. Since IEEE 802.15.6 does not consider the remaining energy of relay nodes, the energy consumption increases resulting in shorter network lifetime.

The average delay of the proposed scheme and IEEE 802.15.6 as a function of the percentage of link loss is shown in Fig. 9. The proposed scheme shows lower delay compared to IEEE 802.15.6 due to the fact that it considers traffic load as a link quality. Both Scenarios 3 and 4 give higher weight to the average SNR value, and this results in better performance. Scenario 4 assumes an emergency situation, which requires low delay and high reliability, and hence average SNR and traffic load are highly weighted. Consequently, this leads to the lowest delay for Scenario 4.

In summary, IEEE 802.15.6 shows the worst performance in terms of PRR, average power consumption, network lifetime, and average delay since it does not consider how a relay node should be selected. In contrast, the proposed scheme dynamically selects relay nodes using AHP, which considers average SNR, traffic load, and remaining energy, and thus guarantees high reliability, low power consumption, and low delay. As a result, the proposed scheme can flexibly satisfy various requirements for different scenarios in WBANs.

6 Conclusion

WBANs need to provide ultra-low power consumption and reliable communication between the coordinator and sensor nodes. However, due to characteristics of the body medium and postural body movements in a WBAN, link loss frequently occurs causing additional energy consumption and unreliable communication. To cope with these issues, this paper proposed an AHP-based Flexible Relay Node Selection scheme for WBANs, which can be adaptively applied to various situations leading to lower power consumption and delay as well as more reliable data transmission. Our simulation results verify that the proposed scheme significantly improves the power consumption and the reliability of the system compared with the conventional IEEE 802.15.6 scheme.

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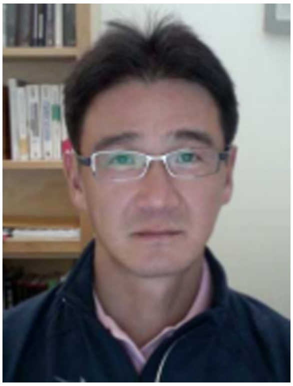

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