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Link Reliability and Performance Optimization in Wireless Body Area Networks

KEFA G. MKONGWA, QINGLING LIU, AND CHAOZHU ZHANG
College of Information and Communication Engineering, Harbin Engineering University, Harbin 1500001, China

Corresponding author: Qingling Liu (liuqingling@hrbeu.edu.cn)

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ABSTRACT Wireless body area networks (WBAN) require long life links and energy efficient system. Besides the increasing commercialization of WBAN, health monitoring applications calls for enhanced quality of service (QoS). The establishment of the reliable and energy efficient link is crucial to support the improvement of the WBAN performance parameters. In this article, we propose a cross-layer routing mechanism for WBAN quality of service enhancement. The protocol uses a cost function, which linearly combines node energy ratio, link reliability, and specific absorption rate functions. The proposed algorithm initially maximizes network lifetime longevity by reducing node energy consumption with nearly reasonable throughput and the packet delivery ratio whereas the enhancement of the QoS focused on improving network throughput and the packet delivery success rate for WBAN applications. The algorithm is implemented in two stages, firstly by designing the energy efficient and reliable link routing policy in the network layer and secondly the adjustment of the contention window for QoS performance enhancement in the data link layer using IEEE 802.11 medium access control (MAC) protocol. We conduct parametric modeling of the cost function to analyze network performance in different parametric combinations and contention window adjustments. Simulation results show the proposed protocol improves network performance indicators such as energy efficiency, lifetime longevity maximization, throughput, and packet success delivery ratio.

INDEX TERMS Contention window (CW), energy efficiency, link reliability, quality of service (QoS), wireless body area networks (WBAN).

I. INTRODUCTION

The escalation in sensor technology and wireless sensor networks (WSN) promotes the efficiency of healthcare services. To date, miniaturized sensors deployed in different parts of the body are widely used for remote vital health signs monitoring. The integrated biological sensors use radio links to build wireless body area (sensor) networks (WBAN/WBSN), a technology which can gather, process, transmit, and save sensor data composing patients' physiological signs. A remote health facility uses WBAN acquired data to prognose the health situation for medical and nonmedical purposes [1]. In medical applications, WBAN deployment fosters preventive health measures and primarily reduce patients' hospitalization, movement, and rehabilitation program charges [2], [3].

The poised WBAN commercialization faces several challenges regarding the body sensor circuitry portability, battery size, battery lifetime, sensor bio-compatibility, reliability, and network QoS. Body sensors are deployed as implants, surface contacts, or wearables. Hence, based on the sensor placement, coordination of WBAN faces several constraints, including transmission power requirement, body tissues heating and signal attenuation due to shadowing, anomalies, interference and specific absorption rate (SAR) of body fluids [4], [5].

In WBAN, data communication requires guaranteed QoS, which takes into an account network traffic dynamics on priority and nonpriority based services (e.g., on emergencies). QoS in WBAN is considered based on the set performance criteria, including energy efficiency, network lifetime, low data rates, delay, packet delivery success rate, and link reliability [6]. Achieving better QoS performance metric depends on the application context and reliable connections, which also rely on the node energy consumption

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during transmission. Link reliability may be affected by the extreme packet collision, link dropout, and node outage. While most of the existing WBAN protocols, mainly focus on energy efficient routing and lifetime longevity maximization in the network layer, these protocols have little effect in terms of reduced packet collision and packet delivery success rates [7]. In general, routing protocols must consider the trade-offs between energy efficiency and performance enhancement, which in most cases is difficult to achieve both at a time.

Deployment of low-level protocols complements for energy efficiency and lifetime maximization with the network performance metric enhancement. Several MAC and other cross-layer protocols which cooperatively joins the MAC in the data link layer and the lower and upper layers have been used for network performance enhancement. Adjusting MAC mechanisms which integrates the PHY layer and other top layers have primarily boosted performance enhancement of the wireless networks [8], [9].

For health monitoring, achieving WBAN quality of service with all the performance metrics is crucial. In this view, enhancement of the network performance metrics remains as one of the exciting research fields. The contribution of this work focus on three main areas;

i. Use of the alternative link reliability optimization criteria in improving energy efficiency and network lifetime longevity maximization.
ii. Integrating tissue-specific absorption (low SAR) when modeling for a reliable link during network operation to ensure reduced thermal effect and radiation hazards over the time of exposure.
iii. Adjustment of the contention window mechanism in the MAC layer to boost WBAN performance metrics.

The organization of this work consists of the following sections; section (II) discusses related practices for link reliability, and QoS enhancement criteria, section (III) describes the proposed methods, section (IV) gives a detailed simulation setup, section (V) results and discussion, and the conclusion in section (VI).

II. RELATED WORKS

The expanding use of WBAN devices in various application areas identifies additional requirements by users, including device comfortability, portability, fault assurance, security, reliability, and quality of service [10]. Besides the main device objective for health monitoring, users expect more convenience on different states of their body posture and movement. WBAN link reliability depends on the sensor working environment, visibility, and instant node residual energy. Based on the application context WBAN resources may be scarce. So maintaining the system quality over time can be affected by the fluctuating network traffic, extreme packet collision, and limited node transmission energy [11].

WBAN topology consists of few nodes configured through a direct or cooperative relay mechanism. For randomly distributed WBAN sensors, point to point transmission power requirement takes into account the euclidean distance between the source and the master node considering media path losses. On this basis, link reliability depends on the sensor position in the body and the energy efficient network configuration [12].

Since WBAN sensors are battery-powered devices; their network performance mainly requires efficient batteries to support longer network life. Based on the battery size limitation, the use of alternative energy efficient routing reduces network energy consumption [13]. In most cases, the use of cooperative multihop relay technique reduces transmission power requirement due to the shorter transmission distance between relay nodes. In [14], the authors propose a cooperative relay mechanism for energy efficiency and performance enhancement of intra-body communication whereas the authors in [15], proposed the network lifetime extension mechanism using surface body contacts and wearables as relaying elements between body implants and the master node (In to Out (I2O) communication). In most energy efficient protocols, packet routing base on the instant node remaining energy as the primary requirement and cooperative relaying; however, they are insufficient criteria for selecting the next hop for packet forwarding. Despite the extensive use of node distance and the instant remaining power in different protocols [16]; these protocols lack considerations for the link path loss [17]. In [18], apart from the conventional energy efficiency and lifetime maximization methods using node distance to the coordinator, authors pointed out that the distribution of WBAN nodes over the monitored surface require alternative energy efficiency approach. So, the energy difference between adjacent nodes was used to model a routing policy which considers the transmission energy requirement to maximize energy efficiency and network lifetime.

Besides node distance and residue network energy, packet collision have always been one of the biggest challenges in WBANs. Packet collision has effects including link dropout and extreme network delays whereas the re-transmission of the colliding packets poises for additional network energy requirement. Additionally, more extensive networks increase channel contentions in the shared media, which, in return, causes packet collision [19]. In the typical data transmission scenario, packet collision degrades packet delivery success. So, adjusting MAC mechanisms on the contention window, back-off or collision avoidance reduce energy requirement and network resource competition during an emergency and regular data transmission [20]. In [21], the authors used a back-off mechanism to adjust the timing in a contention-free time division multiple access (TDMA) MAC, which reduced packet collision probability. Further to that, they applied Markov Chain model to reschedule unsuccessfully transmitted packets and network performance estimation. The approach enhanced network throughput among sensors in the inter-WBAN networks.

On the other hand, larger data frames demand more network resources, and different nodes generate packets with varying data rates, which raise the unbalanced network resource requirement. Authors in [22] use improved sensor MAC (S-MAC) to automatically adjust the contention window size based on the network load when enhancing WBAN energy efficiency and QoS metrics. For the composite data generation, the backoff period in [23], is modified to support distinct, minimized, and prioritized range to each traffic during contention for extreme collision avoidance. Authors in [24] use guaranteed time slots (GTS) in IEEE 802.15.4 MAC by swapping between contention free (CFP) and contention access (CAP) periods to provide better network resource management and energy efficiency. Similarly, the packet processing mechanism in IEEE 802.15.4 MAC uses first in first out (FIFO) queuing method, which may increase network delay of the buffered packets and packet loss when delayed beyond limits [25].

Static -TDMA allocates static time slots to nodes. It may in one way enhance fairness in data transmission; however, when a channel is deeply faded, it becomes the most significant constraint even on packet re-transmission. In [26], the authors introduced two approaches in TDMA MAC to enhance network reliability. Firstly, the controller assigns channels to the nodes based on requests upon packet transmission. Nodes which will not receive acknowledgement should consider a transmission channel as a faded one and must go to sleep until next round. To avoid node buffer overflow during sleep time, the controller dynamically assigns a transmission channel based on the load to reduce buffered packet loss.

In the network layer routing protocols are designed based on the selection of the best route for packet forwarding considering node residual energy, hop count, node distance to the coordinator, and link efficiency. In most cases, routing protocols select the path with a fewer number of hops as the best and cost-effective path. However, in [27], authors propose a route with a large number of relays as the best route due to the low transmission energy requirement despite the network initial costs and delay. The protocol takes into consideration the link efficiency, distance between nodes, the number of hops, and the node residual energy into a cost function. Since for direct links, remote nodes need more transmission energy compared to closer nodes, a route with many intermediate devices is most likely to give more energy balance than the shortest path.

Node participation in data transmission or relaying determines its energy requirement during network operation. Since network functions involving packet transmission, overhearing, and idle listening consumes more power, authors in [28], assessed node energy consumption based on the packet transmission frequency. To extend the network lifetime, they adjusted the contention window to adapt the packet relaying or generation rate for collision avoidance during a regular situation and emergencies. Another criterion used to assess node involvement in network activity is by comparing active and inactive spans of the duty cycle. In the MAC layer, the duty cycle can be planned based on the busy and sleep time of the node. Protocols like S-MAC have a fixed duty cycle, so it is rare to adjust its performance criteria with traffic and topology variation as compared to IEEE 802.11 MAC [29].

The data transmission mechanism is an application demand specific. In some applications, the transmission of the monitored physiological parameters can be categorized as random or periodic. So networks with low latency and higher reliability are highly demanded in such a situation to avoid collisions and interference between WBAN coexistence. In [30], the authors proposed a hybrid multichannel MAC protocol to improve network throughput. The algorithm integrates carrier sense multiple access with collision avoidance (CSMA/CA) with TDMA MAC to distinguish network resources for random access from periodic data, respectively.

The growing interest in WBAN mobility poses many questions for link stability of the mobile networks. Since the existence of energy efficient link has stability uncertainty, the authors in [31], proposed energy saving and a stable routing protocol for inter-WBAN communication. The proposed method takes into consideration the node residual energy and its distance from the sink into a cost function. In the algorithm, route selection considers a maximum objective function of each node participating in packet forwarding for distributed WBANs.

Based on the literature of the previous studies, most research papers focus on performance enhancement considering node energy consumption and network throughput, which hardly withstand varying data rates. Also, there is little consideration for the radiation effect of the radio devices embedded in biological sensors for hazard-free energy-efficient path selection during the network operation.

III. PROPOSED METHOD

The main goal of this work is to offer an alternative routing protocol, which contributes to energy efficiency and performance enhancement of the WBANs. Our primary focus is the provision of a reliable and stable route, which subsequently provides low SAR network lifetime extension and energy efficiency. The secondary objective is to improve the network performance in terms of packet delivery success and throughput for varying data rates. In this article, we improve network performance by adjusting the contention window and the backoff period in the MAC of the data link layer.

Firstly, WBAN route initiation starts with the source node by sending route requests to its neighbors. In a cooperative relay mechanism, neighbors with a valid route to the destination will forward the route requests to other nodes in the direction of the destination node until the path is determined. Each node with an authentic route to the destination will send a route reply to the immediate source or relay node. Based on route request and reply, source nodes can establish a path to the destination.

Most conventional routing protocols hardly consider node energy and path reliability as a criterion for route selection. Different algorithms use several rules basing on the sequence number or shortest distance between source and destination to establish the best route. The shortest distance is estimated using the hop count between source and destination. Selection of the route is either controlled through the source node or a routing table whose variables describe routing parameters of the nodes in the prospective path. Since all information about the proposed valid route is updated, nodes would beware of the health status of the most current or fresh route and the neighbors.

For better route selection with assurance for improved energy efficiency and lifetime maximization, additional parameters are added into the routing table in every transmission so that the route selection process considers additional factors. Additional settings in the routing table supporting route selection criteria may include, among others; node residual energy, node distance, received signal strength and the specific absorption rate.

A. STABLE ROUTE ESTABLISHMENT

Our proposed protocol takes into consideration the node distribution over the monitored area, where individual node distance from the master node determines the energy requirement for packet transmission strategy and a reliable link establishment criteria. Additionally, in every node activity, dissipated energy has a heating effect, which may cause poor performance of the sensor circuitry or several health risks to monitored individuals. So, the establishment of a reliable link considers three main additional parameters in the routing table, namely; energy ratio, node distribution over the monitored surface, and a specific absorption rate.

1) ENERGY RATIO

Energy is the primary requirement for WBANs in supporting various tasks, including signal detection, processing, transmission, and during idle listening. Network lifetime primarily depends on the node residual energy level. In each network operation node energy depreciates, so the selection of the best routing algorithm leverage for energy requirement. During sleep time and idle listening, nodes consume less energy compared to the energy required during transmission, signal detection, and processing. Thus, avoiding frequent battery replacement, node energy management must consider deploying relevant energy efficient algorithms. In this article together with other requirements, link lifetime is estimated using node energy ratio, which confines its rate in the range between 0 and 1 given by the relation in (1).

$$E_R = \frac{residual\ node\ energy}{initial\ node\ energy}. \tag{1}$$

where $\boldsymbol{E_R}$ is the node energy ratio, $\boldsymbol{E_R}$ is the probability used to estimate node lifetime in the network. The node energy ratio as an indicator for the battery draining rate depends on many factors, including node activity as a fully functional or reduced function device, design material, and operating temperature. Nodes with higher energy ratio have a higher probability of being included in the most preferred route.

2) LINK RELIABILITY

WBAN QoS depends on the authenticity of the link where stable and a long life link ensures maximum packet transmission over a long duration of time. Permanent links have sufficient energy to support communicating nodes and therefore reduce the link and packet drop rate. Since transceivers consume more power during transmission as a result of transmission frequency or distance, link reliability takes into account node distribution around the coordinator. Reliability function enumerates relative node standard deviations around the master node as applied in [31]. Smaller node deviation ensures more link stability due to shorter transmission distance and power requirement for packet communication. The normal distribution function is used to estimate node stability for transmission and signal detection. Equation (2) evaluates mean distances between nodes and the master node.

$$N_{\mu d} = \frac{\sum\limits_{i=0}^{i=n} d_{nc}(n_d, c_c)}{n} \tag{2}$$

where;

$N_{\mu d}$: is the mean node distances

n: is the total number of nodes

d_{nc}: is the node-coordinator distance (Euclidean distance)

n_d: node position (x,y)

c_c: coordinator position (x,y)

Standard deviation estimates node distribution around the coordinator. Where $\boldsymbol{d_{nc}}$ and $\boldsymbol{N_{\mu d}}$ are euclidean and mean distances, respectively, node standard deviation is evaluated using (3).

$$N_\delta = \sqrt{\frac{1}{n}\sum\nolimits_{i=0}^{n} (d_{nc}(n_d, c_c) - N_{\mu d})^2} \tag{3}$$

where; N_δ: node standard deviation.

Normalized standard deviation gives an estimate of the relative distribution of nodes around the coordinator. Reliability function ($\boldsymbol{L_r}$) is computed as a relative normal distribution [0,1] of the nodes around the master node given by (4).

$$L_r = \frac{N_\delta}{N_{\mu d}} \tag{4}$$

Based on (2), (3) and (4), variations of the mean node distance to their standard deviations around the coordinator determines the stability of the communication link. A reliable and stable communication link depends on the transmission distance between communicating devices as a requirement for transmission power.

The link reliability function ranges between 0 and 1, showing node distribution around the master node. Therefore link stability is defined by the following decision indicator, where the route with maximum reliability function is desired.

$$If\ \boldsymbol{L_r} \approx \begin{cases} 0 & A\ more\ stable\ link\ as\ it\ tends\ to \\ & 0:\ proper\ node\ distribution. \\ 1 & The\ less\ stable\ link\ as\ it\ tends\ to \\ & 1:\ poor\ node\ distribution. \end{cases}$$

We compute the maximum link reliability by taking the inverse reliability function as of (5).

$$Max(L_r) = \left|\frac{1}{\mathrm{L}_r}\right| \tag{5}$$

Appropriately node distribution around the coordinator implies smooth packet communication. Nodes involved in persistent network activities keeps the monitored organ susceptible to radiation hazards due to thermal emission. To further stabilize the nodes from the heating effect as well as ensuring controlled parts' radiation safety, the link reliability function is complemented by including the specific absorption rate (SAR).

3) SPECIFIC ABSORPTION RATE (SAR)

WBANs use radio devices operating in radio frequency. As part of the electromagnetic wave spectrum, radio waves propagation is obstructed by the body tissues due to the absorption properties of body fluids. Nodes involved frequently in network activities emit more radiation resulting in heating effect, which may raise the body and the sensor circuitry temperature. Heated sensor circuit hinders its regular operation, the rising body temperature discomforts users, and may lead to other biological side effects, including enzymatic disorders. The SAR value must be kept very low to avoid such complications.

In our proposed model, we incorporated the SAR estimation below the international standard limits set by the international commission on nonionizing radiation protection (ICNIRP, SAR $\leq$ 2J/Kg/s for 10g of tissue). The SAR function (S_f) is evaluated using (6).

$$S_f = 1.2 - SAR_{ratio} \tag{6}$$

where $\mathrm{SAR}_{\mathrm{ratio}}$ is given by,

$$SAR_{ratio} = \frac{SAR}{SAR_{\mathrm{lim(ICNIRP)}}}$$

Also, SAR is given by,

$$SAR = 2 * \frac{Consumed\ energy}{weight_{tissue} * time}$$

The linear combination of the energy ratio, link reliability function, and the specific absorption rate defines the cost function for energy efficiency and lifetime maximization with low SAR WBAN. As the energy ratio controls the network energy and lifetime, link reliability takes control of the stable link, lifetime longevity and performance matters in support of the SAR limits. The maximum cost function is a parametric combination of the node energy ratio, link reliability, and SAR functions. The use of parametric values in the cost function implies variations in the quality of battery life and materials ($\mathbf{r_1}$), the quality of the established link ($\mathbf{r_2}$) and the thermal effect coefficient ($\mathbf{r_3}$) during network operation where the summation of the parametric values is always 1 [31]. The maximum cost function is given by (7).

$$\cos t = r_1 E_R + r_2 \left|\frac{1}{L_r}\right| + r_3(1.2 - SAR_{ratio}) \tag{7}$$

where,

$$r_1 + r_2 + r_3 = 1$$

4) ENERGY EFFICIENCY AND LIFETIME MAXIMIZATION ALGORITHM

During route establishment, source nodes will initiate packet link to the master node considering the next hop selection among neighbors conforms to the criteria for energy efficiency and lifetime extension. In every route update, routing table updates information regarding node residual energy level, the maximum cost function, hop count, and the sequence number. Route selection is such that if a node is near the coordinator, it can transmit packets directly else may cooperatively use relay nodes. Since nodes may be shadowed depending on the deployed position (e.g., Arms position in motion), the use of relay node is inevitable although in our article the proposed network architecture qualifies each node for direct transmission alternative.

On the route establishment, the source node identifies its neighbors and forward route request. Neighbors with a valid route to the destination will send a reply expressing their energy ratio for packet transmission, sequence number, hop count, and maximum cost function. Network paths whose nodes have more energy become a priority when establishing an instant stable route. Pseudocode 1 gives a summary of a stable route establishment algorithm.

B. QOS METRIC PERFORMANCE ENHANCEMENT

Apart from network lifetime longevity maximization, the route selection criterion for energy efficient WBANs faces several QoS constraints. Some of the challenges include the extended propagation delay of buffered packets in the source and relay nodes since the network prioritizes optimum routes. Longest queues may end up with a degraded network throughput and the packet delivery success rate. Despite the best link reliability, the system can provide for an extended network lifetime, provision of the best performance metrics complement the quality of service requirement for life sensitive health monitoring networks.

Since WBANs forward packets of varying data rates, depending on originating signal sources, it requires sufficient supporting network infrastructure and better QoS. The proposed protocol uses the IEEE 802.11 MAC standard for WBAN QoS enhancement. MAC sub-layer is responsible for interconnecting the physical layer and upper layers in the open system interconnection (OSI) model. MAC has functions including transmission error detection and correction, scheduling of node sleep time, idle duration and packet retransmission, adjustment of the contention window and channel assignment using CSMA/CA and TDMA respectively. A slight modification of MAC mechanisms and parameters can exceptionally improve network performance.

IEEE 802.11 MAC use contention-based channel access with collision avoidance, the protocol highly reduces packet collision and energy consumption due to reduced

Pseudocode 1 Describing Energy Efficiency and Lifetime Maximization

```
If(ready){
Source→sends hello msg
Neighbors→send ACK
Source→update neighbor list
          send request
Neighbors→compute: hop count, sequence #,
          Energy ratio, SAR, Reliability function, Link
          cost function.
          →send reply
If(Source→receive reply){
Route update:
If(neighbor:residue energy ≥ thresh, link cost function ≥
    max(cost function))
  Hop count == low, sequence # (same or fresh))
  Update routing table
End
Route selection:
 if(hope count and sequence # conforms)
   if(residue energy ≥ thresh && link cost function ≥
     max(cost function)
      Update route,
      Forward packets,
   End
 End
Route expiration:
  If(route: not expired, residue energy ≥ thresh && link
     cost function ≥ max(cost function))
   Forward buffered packets
  Else
   Drop packets
   Purge route
  End
End
 }
End
}
Repeat
```

packet re-transmission. The integration of the MAC protocol with upper layer protocols may face performance constraints, including excessive queues, which increases packet drop rates. Since WBAN forward packets with different data rates, the available network resource is insufficient. In this work, the contention window is adjusted to accommodate different data rates.

1) CHANNEL CONTENTION IN MAC

IEEE 802.11 MAC has three mechanisms; contention window adjustment, back off mechanism, and collision avoidance [32]. In a contention-based system, channel access competition depends on the number of nodes in the proposed network. A node accessing the channel is assigned a network allocation vector (NAV) defined as the time duration which other nodes wait until the current node finishes packet transmission. When one node is accessing the channel, the rest of the nodes remain without contention until the NAV expires. On this basis, IEEE 802.11 MAC may fail to handle emergencies due to varying data rates from different sources which require more network infrastructure. Apart from handling medium access fairly conventional IEEE 802.11 MAC (under distributed coordination function) cannot adequately meet the QoS requirement.

Initially, depending on the frame size nodes are assigned a minimum contention window (CW) for packet transmission. The minimum CW size is a random number set between 0 and $\mathrm{CW}_{\min}$, $[0, \mathrm{CW}_{\min}]$. On each transmission failure, the CW doubles until its retry limit [32], [33]. In each successful transmission or on a retry limit the contention window resets to its minimum value, and the channel contention starts again. Since the size of the CW determines the collision probabilities at each time step, larger CW has lower chances for the collision. With larger CW, more nodes are allowed for channel contention and hence raising energy requirement. However, in the proposed algorithm, the use of stable routing and CW adjustment protocols cooperatively reduce node energy consumption.

In our work, we propose an adjustment criterion for the contention window size and the backoff period. Whenever nodes have enough energy, and a stable link exists between nodes in the selected path, then the network should be able to support maximum possible data rates. We propose four different adjustments of the contention window based on the functions: 1, 2, 3, and 4. The contention window size doubles after every transmission success or collision according to the exponential backoff period given by $2^{\mathrm{i+k}} - 1$ where $\boldsymbol{i} + \boldsymbol{k} = 10$. '$\boldsymbol{i}$' is an integer between 1 and $\boldsymbol{n}$, where '$\boldsymbol{k}$' is constant. For this case, if $1 \leq \mathrm{i} \leq 6$, $\mathrm{CWmin} = 31$ and $\mathrm{k} = 4$ then $\mathrm{CWmax} = 1023$, therefore, there are only 6 retransmission attempts before a packet is dropped where the possible CW values are: {31, 63, 127, 255, 511, and 1023}. Increasing the size of the CWmin provides a room for multiple nodes accessing a channel and reduce collision probabilities during the CAP. However, nodes suffer from large packet buffer and delay. To reduce hindrance from excessive buffer and delay, we modified the CW increment function by adding a constant value $((\mathrm{CW} << 1) + 3)$ to the binary left shift operator. The modification of the CW increment function widens the CW size and reduce retransmission attempts while saving more energy [33].

In function 1, adding 3 to the left shift operator further extend the span of the CW size to support more transmission channel access, reduce packet queues and the retransmission attempts.

Further, in function 2, the CW increment function was modified such that the maximum contention window is limited to reset at its three-quarters of the actual maximum value. The number of retransmission trials reduces further, giving more possibilities for energy saving at some parametric combinations. In Function 3, we use the combination of function 2 and on every CW reset the minimum contention window is doubled to allow more nodes contending for channel access. Although, improvement of the performance parameters demands more energy to support packet transmission when CW becomes wider. So, in function 4, we further adjusted the backoff period based on the implementation of function 3 to reduce delay and packet drop rate. As the performance enhancement is so complicated based on the interdependence between different metrics, the implementation of the functions gave a better comparative analysis of the proposed model on various parameters. The proposed CW adjustments are as illustrated in functions: 1, 2, 3, and 4 whose general characteristics based on appropriate parametric combination are summarized in Table 1.

TABLE 1. Modified CW increment function general characteristics.

Increment function and CW range	Retransmission attempts	Significance
Function 1 (f1): CW = (CW<<1) + 3 **CW Range:** [CWmin, CWmax]	Higher	• High energy demand • Average lifetime • Moderately higher packet delay and buffer
Function 2 (f2): CW = (CW<<1) + 3 **CW Range:** [CWmin, 0.75*CWmax]	Medium	• Average energy demand • Slightly higher lifetime • Average packet delay and buffer
Function 3 (f3): CW = (CW<<1) + 3 **CW Range:** [2*CWmin, 0.75*CWmax]	Low	• Low energy demand • Finer lifetime • Low packet delay and buffer
Function 4 (f4): CW = (CW<<1) + 3 **CW Range:** [2*CWmin, 0.75*CWmax] DIFS = (2*DIFS)	Low	• Low energy demand • Finer lifetime • Lower packet delay and buffer

Function1: adding 3 to 1 bit left shift

```
void inc_cw()
{
CW = (CW << 1) + 3;
If (CW > CWMax)
CW = CWMax;
}
```

Function 2: adding 3 to 1 bit left shift and setting CWMax = 0.75*CW maximum.

```
void inc_cw()
{
CW = (CW << 1) + 3;
If (CW > CWMax)
CW = CWMax;
If (CW < CWMax)
CW = 0.75*CWMax;
}
```

Function 3: adding 3 to 1 bit left shift and setting CWMax = 0.75*CW maximum.

```
void inc_cw()
{
CW = (CW << 1) + 3;
If (CW > CWMax)
CW = CWMax;
If (CW < CWMax)
CW = 0.75*CWMax;
}
Void rst_cw ()
{
CW = 2*CWMin;
}
```

Function 4: double the backoff period, keeping CW max reduced by 25%.

```
(a) void inc_cw()
    {
    CW = (CW << 1) + 3;
    If (CW > CWMax)
    CW = CWMax;
    If (CW < CWMax)
    CW = 0.75*CWMax;
    }
    Void rst_cw()
    {
    CW = 2*CWMin;
    }
(b) checkBackoffTimer()
    {
    If(idle && backoff-paused)
    {
    // DIFS = DCF Interfame Space
    // DCF = Distributed Coordination Function
    Backoff-resume(2*DIFS)
    If(!idle && backoff-busy && !backoff paused)
    Backoff-pause
    }
```

IV. SIMULATION SETUP

We designed and simulated a WBAN network consisting of 8 source nodes and 1 coordinator, as shown in Fig. 1. Nodes are deployed on the chest, abdominal part, and arms. Each node is at an allowable transmission distance to the sink node; however, the node distances from the coordinator and between each other are nonuniform. We simulated our proposed WBAN protocol using Network simulator 2.35 software. We assign 50J of energy to each source node except the sink node, which is assigned 100J due to its multiple activities. As the allowable data rate in WBAN is between 10 Kbps to 10Mbps, we set the packet generation rate at 50Kbps with a packet size of 500 bytes for a simulation time of 120s.

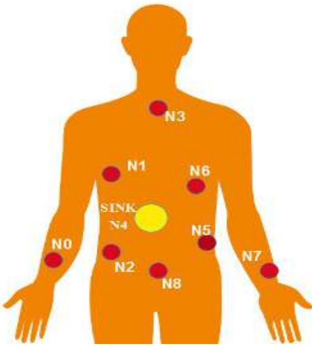


FIGURE 1. **Proposed WBAN topology showing body sensor distribution.**

Depending on the state of link stability and energy availability in source nodes, nodes may opt to use a cooperative relay mechanism to communicate with the master node based on the prevailing conditions.

V. SIMULATION RESULTS AND DISCUSSION

We simulated the proposed protocol in two stages; firstly the simulation focused on the implementation of performance enhancement and link stability of the routing protocol and secondly, the implementation of the quality of service enhancement by contention window adjustment in the MAC.

Before undertaking the proposed protocol performance analysis in different scenarios, section A gives a logical implication of the relationships between selected parametric values in the cost function with the performance indicators. Parametric values are trivial values chosen randomly in the interval between 0 and 1 in a condition that selected values must sum up to 1 (i.e $r_1 + r_2 + r_3 = 1$). Selected parameters as modifiers (r_1: energy ratio, r_2: link reliability and r_3: SAR) are linearly combined in the cost function to modify the response of the proposed model in varying operational and environmental conditions. Identification of parameter relationship with performance indicators considered each parameter independent of the other (keeping other parameters constant). When implementing individual parameters, the response of the respective indicators varies from one another, where some of the indicators perform better in the cost of the poor performance of the other. The simulation results show that encountering such trade-offs, the use of more than one parameter in the cost function is necessary.

On protocol performance analysis, firstly, the WBAN simulation based on the parametric variations of cost function variables considering the node energy ratio, link reliability, and the specific absorption rate without adjusting the contention window. Initially, the protocol showed the best performance in terms of energy efficiency and lifetime longevity maximization, although further QoS performance enhancement is also necessary. The QoS enhancement combines the parametric variations of the cost function with the minimum contention window adjustment to allow more nodes to contend for channel access.

By using the reliability, SAR, and energy ratio function, the routing protocol opt for a stable and energy efficient route resulting in better network performance. Simulation results show different network performances in energy efficiency, lifetime maximization, throughput and packet delivery success rates on several trivially selected parametric combinations, which is by far better than the implementation of the same architecture using conventional protocols. The application using the standard protocol showed simulation results with a network lifetime of 93.1 s, throughput of 0.655Kbps, a packet delivery success rate of 0.866, and residue network energy of 63.31Joules after simulation time.

Sections B and C, compares the proposed protocol performance in terms of parametric variations of the cost function before and after the adjustment of the contention window to show different criteria for WBAN performance improvement.

A. NETWORK PERFORMANCE INDICATORS' DEPENDENCY ON PARAMETRIC VALUES

1) NETWORK RESIDUE ENERGY

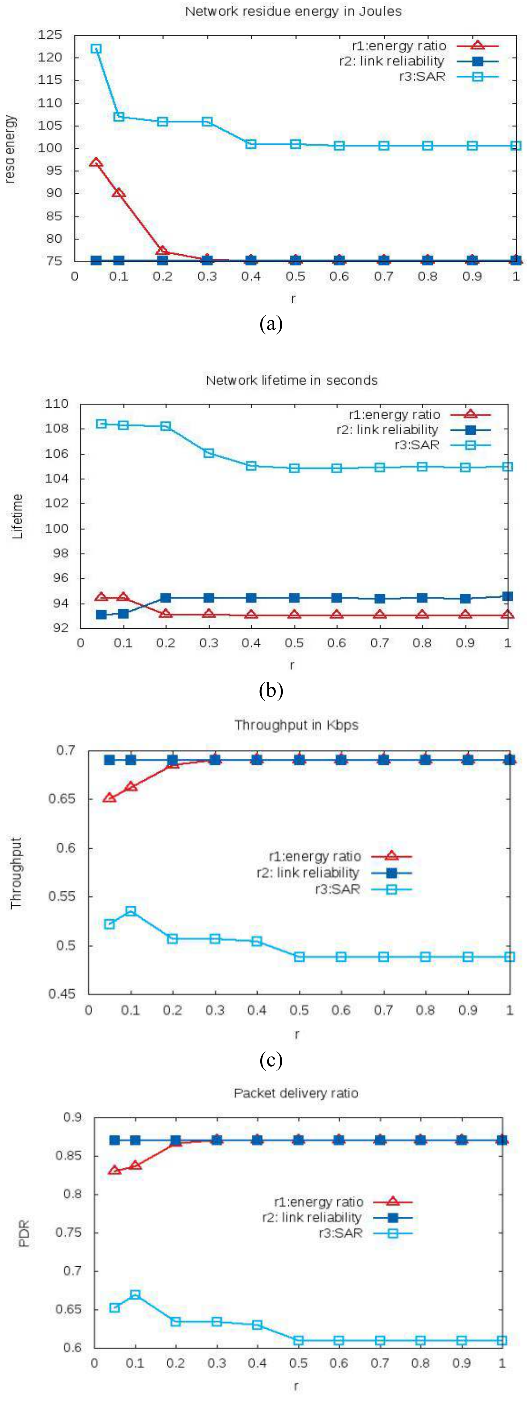
Network energy loss results from higher SAR, among other factors. Keeping low SAR reduces energy loss through heating and radiation emission. Selection of the optimum route depends on the residue energy threshold and the maximum cost function. As higher SAR result in higher energy consumption, its modifier (r_3) must be small to allow more energy saving. Setting low r_1 and r_3 results in more residue energy, whereas r_2 show minimal variation in network residue energy with different coefficient values. r_2 is mainly concerned with the lifetime rather than energy efficiency enhancement, as demonstrated in Fig. 2(a). Also, residue node energy decreases with an increase in r_1 since the initial node energy is always constant, refer (1). Mathematical synthesis of the residue energy relationship with r_1 is further supported by substituting (1) into (7) keeping other factors constant (say $r_2 = 0$ and $r_3 = 0$) as stipulated in (8) and (9).

$$\cos t = r_1 \left(\frac{residue\ node\ energy}{initial\ node\ energy} \right) \tag{8}$$

$$residue\ node\ energy = \left(\frac{\cos t}{r_1} \right) * initial\ node\ energy \tag{9}$$

2) NETWORK LIFETIME

Network lifetime is limited by energy scarcity. Node residue energy in relation to its consumption rate derives its lifetime. In the proposed model, residue energy decreases with an increase in r_1, and so does the lifetime. Since link reliability modifies the link availability and therefore, the lifetime, an increase in lifetime longevity increases with the value of r_2 as depicted in Fig. 2(b). However, r_1 and r_2 complement each other. Since lower SAR gives more energy saving, so it decreases with an increase in r_3 as lower SAR provides more network lifetime. Where $\boldsymbol{t}$ is the network lifetime, $\boldsymbol{e_i}$, $\boldsymbol{e_r}$ are the initial and residue node energy respectively, and $\boldsymbol{C_t}$ is the



(a)

(b)

(c)

(d)

FIGURE 2. **Relationship between cost function parametric values with: (a) Network residue energy, (b) lifetime longevity maximization, (c) Network throughput, and (d) packet delivery ratio(PDR).**

cost, then network lifetime is given by,

$$t = \frac{initial\ node\ energy}{consumed\ energy} = \frac{e_i}{e_i - e_r} \tag{10}$$

Then,

$$e_r = e_i * \left(\frac{t-1}{t}\right) \tag{11}$$

Equating (9) with (11) a relationship between r_1 ant $\boldsymbol{t}$ is deduced as in (12).

$$ln(r_1) = ln(C_t) + \ln(t) - \ln(t-1) \tag{12}$$

where (12) show that r_1 increases with a decreasing lifetime.

3) NETWORK THROUGHPUT

In the proposed protocol, network performance depends on the lower SAR, better link reliability, and residue node energy. As the value of r_1 and r_2 increases, nodes reserve less energy implying the increasing node activities which require more energy for packet transmission. Increasing node activities rise network throughput. The modifier r_3 (SAR) has poor throughput performance compared to r_1 and r_2; this indicates an excellent network performance in terms of its throughput depend mainly on the link reliability and energy ratio functions as demonstrated in Fig. (2)c.

4) PACKET DELIVERY RATIO

The reliable link between nodes supports higher packet throughput as well as the packet delivery success. The variation of the parametric values in the cost function shows that as the value of r_1 and r_2 increases, a more stable link is established while an increase in r_3 destabilizes the connection. Since packet delivery success depends on excellent link stability, in this case, network performance response to parametric values shows an increase in r_2, r_1, and r_3 gives better PDR in precedence order as illustrated in Fig. 2(d).

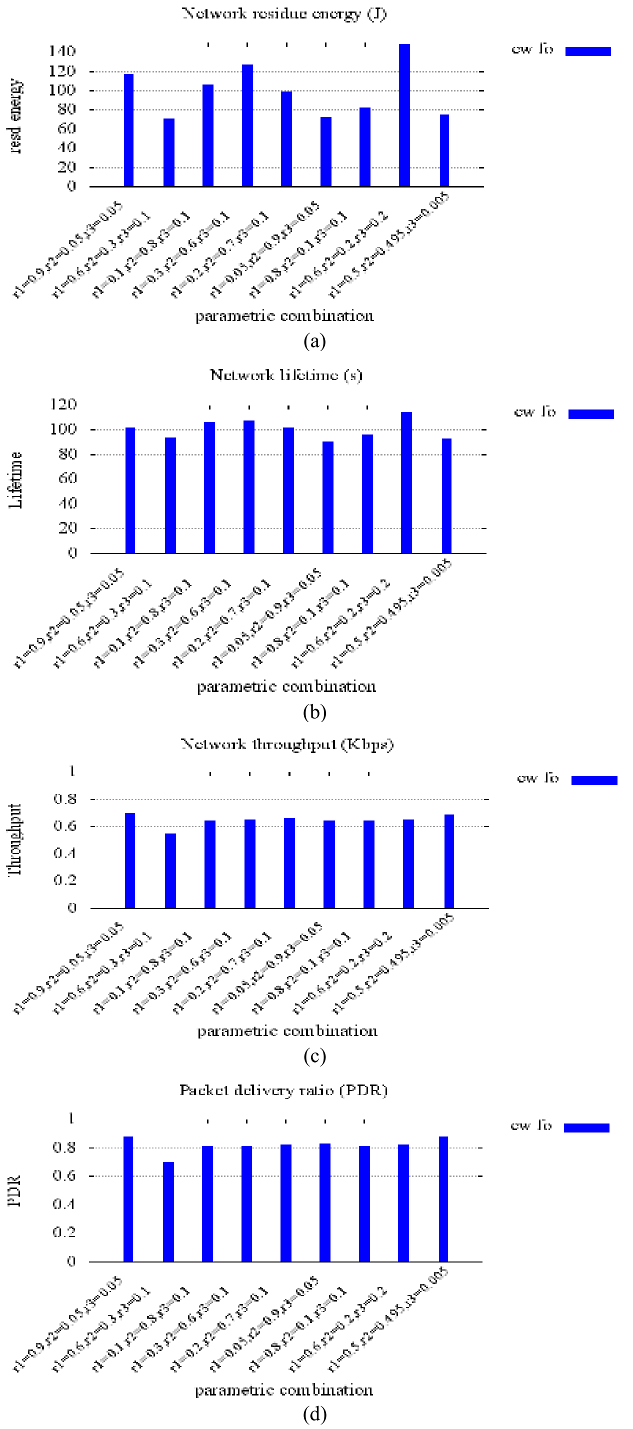
B. NETWORK PERFORMANCE BEFORE CONTENTION WINDOW ADJUSTMENT

1) ENERGY EFFICIENCY

The proposed protocol main focus is to improve WBAN energy efficiency, so during simulation, different parametric values of the cost-function were selected. The comparison shows the best combination of the cost function parameters subsequently reduced node energy consumption during network operation (e.g. r_1, r_2, r_3 = 0.6, 0.2, 0.2). From Fig. 1, node 2 and 5 in respect of their positions were occasionally used as relay nodes for source node 0 and 7 in the arms respectively. These nodes logically consume more energy due to increased network relaying activities. However, some of the parametric combinations ensured the proposed topology remain energy efficient. Fig. 3(a) shows the residual network energy in comparison to its parametric values selected during the simulation. An excellent combination of r_1, r_2, and r_3 cooperatively reduces extreme energy consumption since reliable link reduces packet loss and retransmission rate. Similarly, lower SAR reduces energy loss through radiation.

2) LIFETIME MAXIMIZATION

Efficient energy utilization provides better energy balance, which automatically improves network lifetime. In our design, we considered network lifetime as the time from system power on to the time when the first node is energy



(a)

(b)

(c)

(d)

FIGURE 3. Parametric comparison of the: (a) network residue energy, (b) lifetime longevity maximization, (c) Network throughput, and (d) packet delivery ratio (PDR) of the proposed WBAN topology showing protocol performance with different parametric combinations without CW adjustment (CW fo).

depleted. Simulation results show that in most cases, a network lifetime is independent of either residual energy or link reliability, but a combination of either two or all the three cost function parameters. During the simulation, randomly selected parametric combinations (r_1, r_2, and r_3) in the cost function showed variation in the network lifetime longevity. Parametric combinations with higher residue energy ensured for a longer lifetime. Fig. 3(b) shows a graphical comparison where the proposed algorithm in several parametric values (lifetime $\geq$ 95s) outperformed the conventional protocol whose lifetime is 93.1s.

3) NETWORK THROUGHPUT

The proposed protocol supports a stable link establishment, lifetime longevity maximization, and reduced packet collisions, which improve data rate over the communication network. In some parametric combinations, improvement in network lifetime longevity due to the existence of the stable link and energy efficiency subsequently improved the network throughput higher than 0.655Kbps, as demonstrated in Fig. 3(c).

4) PACKET DELIVERY RATIO

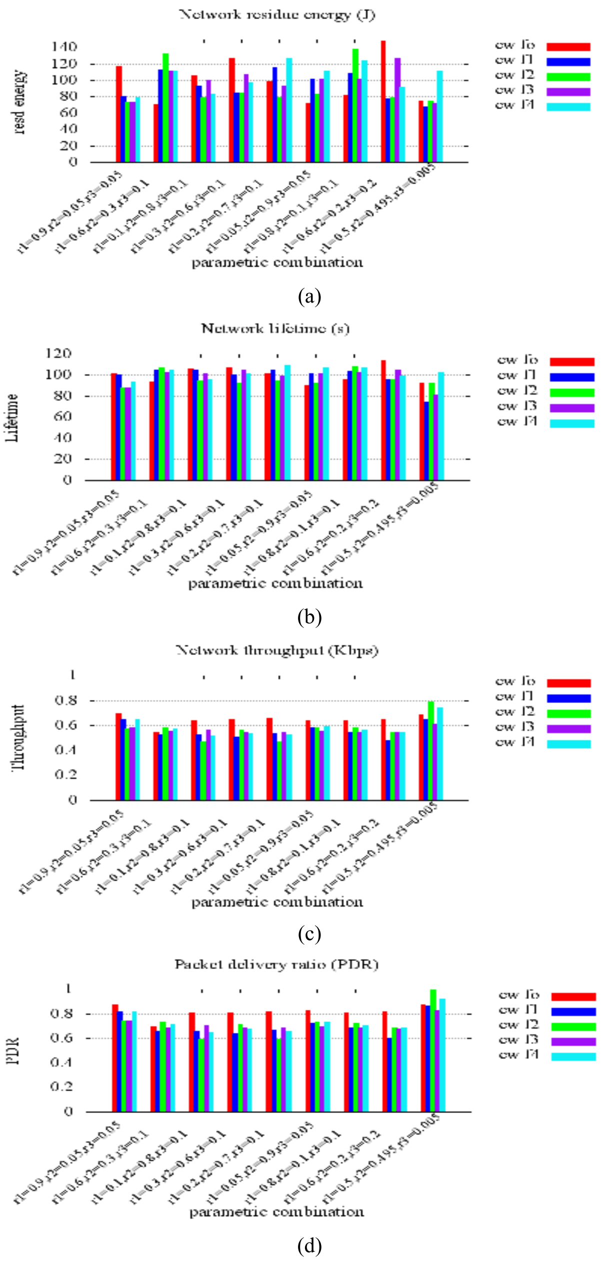
The establishment of long life and the stable link between communicating nodes assures successful packet delivery to the master node. In coordination of adequately selected parametric values, PDR achieves different values, despite the higher energy requirement in separate cases (e.g. $r_1, r_2, r_3 = 0.5, 0.495, 0.005$), as illustrated in Fig. 3(d). However, simulation results show it is not always the case higher PDR involves higher node energy consumption. Sometimes with the same amount of energy, stable and reliable routing may reduce packet collision, delay, and link drop rate hence contributing to higher packet delivery success.

C. NETWORK PERFORMANCE AFTER CONTENTION WINDOW ADJUSTMENT

Scarcity of network resources limits node participation in network activities. Since QoS enhancement is crucial for any WBAN application, achieving better throughput and PDR, require more nodes involvement which logically needs more energy. In IEEE 802.11 MAC, narrow contention window limit node participation to content for a transmission channel during the contention access period. In our work, we adjust the contention window to allow more nodes to contend for channel access during the contention period with minimum collision probability. By using the combination of adjusted CW and parametric variations in the stable route establishment, we obtained different performance results during the simulation. In this section, we have plotted and compared outcomes based on CW adjustment (cw_f_1 - cw_f_4) against the results obtained exclusively of contention window adjustment (cw_f_0).

1) ENERGY EFFICIENCY

Since retransmission of collided particles demands more energy, an adjustment of the CW assures for reduced packet queuing and relief in network resource competition during CAP. However, the demand for transmission energy varies with different parametric combination and CW adjustment



(a)

(b)

(c)

(d)

FIGURE 4. **Parametric comparison of the: (a) node residue energy (b) network lifetime, (c) throughput, and (d) packet delivery ratio (PDR) comparing protocol performance in different parametric combinations before and after contention window adjustment.**

criteria (e.g. cw_f2 and cw_f4). Simulation results show CW adjustment affects energy efficiency due to the increasing packet flow, although in some parametric combinations, extensive CW reduces retransmission attempts hence the energy demand as illustrated in Fig. 4(a). Where, in some cases, the proposed protocol has slightly poor performance compared to that without CW adjustment.

2) LIFETIME MAXIMIZATION

Network lifetime slightly suffers as a consequence of increased energy consumption during CAP due to increased node activities after CW adjustment. Simulation results show that implementation of the functions with wider CW and less packet retransmission trials has improved lifetime longevity in some parametric combinations. Variation in CW adjustment criteria raises varying energy requirement affecting lifetime longevity as demonstrated in Fig. 4(b).

3) NETWORK THROUGHPUT

Adjustment of the backoff mechanism and CW with properly selected parametric values improves QoS performance characteristics. Simulation results in Fig. 4(c) shows that the network throughput enhancement of the proposed cross-layer protocol mainly depends on the proper selection of parametric values and the CW adjustment criteria (e.g. r_1, r_2, $r_3 = 0.5, 0.495, 0.005$). Additionally, using appropriate parametric values, an adjusted backoff mechanism (cw_f4) enhanced network throughput.

4) PACKET DELIVERY RATIO

When there is a stable and reliable network link with CW size increment on each transmission failure, nodes contending for transmission channel increases with reduced collision and delay. Hence, PDR improves with a minimum energy requirement. Fig. 4(d) depicts that at every point where cost function parametric combination improved network throughput, the PDR also increased. However, QoS performance parameters vary from one CW adjustment function to another using different parametric combinations independent of residue energy (e.g. cw_f2 at r_1, r_2, $r_3 = 0.5, 0.495, 0.005$). So from the simulation results, we see that using cross-layer protocols, QoS enhancement depend on the selection of parametric values, type of CW adjustment function, and stable routing mechanism.

VI. CONCLUSION

In this paper, we have designed an energy efficient and stable WBAN link with enhanced performance parameters using cross-layer protocols. We implemented the proposed routing protocol in the network layer and applied QoS enhancement methods in the MAC. QoS indicators of interest were energy efficiency, lifetime longevity maximization, throughput, and packet delivery success rate. We have demonstrated that the establishment of a stable and energy efficient network link depends on the node energy ratio, euclidean distances, and their relative distribution around the master node. Simulation results show that the persistent network link gives assurance for WBAN efficiency in terms of energy requirement and lifetime longevity maximization keeping low SAR. Since robust network application requires extensive network resources, adjustment of the CW and back off mechanisms in the MAC further improves network throughput, PDR, energy efficiency, and lifetime in several parametric combinations. The cooperative implementation of the proposed methods enhanced overall network performance as illustrated in the discussion of the simulation results, although in WBAN performance enhancement, it is not easy to optimize all performance parameters at a time. Instead, the choice of the WBAN application gives priority of the essential performance parameters; therefore, depending on the sensitivity of the WBAN application, different low layer methods can also be applied to support the enhancement of network efficiency besides upper layer protocols. Generally, the methods used in this work provided link stability and significantly improved various network performance parameters.

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KEFA G. MKONGWA received the B.Eng. degree in electronics and communication engineering from the St. Joseph University of Engineering and Technology, Dar es salaam, Tanzania, in 2009, and the M.Eng. degree in signal and information processing from the Tianjin University of Technology and Education, Tianjin, China, in 2013. He is currently pursuing Ph.D. degree in signal and information processing with Harbin Engineering University, Heilongjiang, China.

His current research interests include the Internet of Things, wireless sensor networks, and wireless body area networks (WBAN).

QINGLING LIU received the B.S. and M.S. degrees in signals and information processing from the College of Information and Communication Engineering, Harbin Engineering University, Harbin, China, in 2000 and 2004, respectively, and the Ph.D. degree in computer and software engineering from the Kumoh National Institute of Technology, South Korea, in 2012.

Since 2018, she has been the Deputy Director of the Institute, College of Information and Communication Engineering. Her research interests include wireless network technology, the Internet information security, artificial intelligence, information technology, routing in MANETs, and wireless sensor networks.

CHAOZHU ZHANG received the B.S. degree in electronics and information engineering, the M.S. degree in communications and information systems, and the Ph.D. degree in signal and information processing from Harbin Engineering University, in 1993, 2002, and 2006, respectively.

Since 2009, he has been a Professor with Harbin Engineering University. He is currently an Associate Dean of the College of Information and Communication Engineering. He is also an Academician of the Aerospace Society and a member of the Institute of biomedical, Heilongjiang. His research interests include radar signal processing, biological signal processing, and communication engineering.

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