Journal of Ambient Intelligence and Humanized Computing (2023) 14:6095–6112
https://doi.org/10.1007/s12652-020-02802-5

ORIGINAL RESEARCH

A simple cross-layer mechanism for congestion control and performance enhancement in a localized multiple wireless body area networks

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Received: 21 June 2020 / Accepted: 5 December 2020 / Published online: 27 January 2021

Abstract
Commercialization of the wireless body area network (WBAN) envisions future new normal for WBAN devices coexistence in a localized area. The coexistence may allow devices to freely change positions, associate, or dissociate with the neighbours as users interact. Devices' interaction in a stationary or mobile fashion radiates heat and also competes for the limited network resources resulting to unreliable communication and other performance challenges. Besides alarming user safety, device mobility affects network performance through topology changes, which result to recursive link disconnections, energy waste, packet delay, degraded throughput, and congestion due to excessive control messaging during route repair. In this article, we propose WBAN performance optimization criteria focusing on improving energy efficiency, network throughput, and reducing the end to end delay in multiple existence schemes. Firstly, we propose an alternative routing algorithm, whose routing decision depends on a cost function considering the parameterized residue energy to node distance ratio, link energy reliability, and specific heat absorption in addition to node sequence number and hop count as fundamental route selection metrics. Secondly, we implement congestion control adaptation in the medium access control (IEEE 802.11MAC) mechanism, which improves throughput, reduces congestion, and delay. Due to link discontinuities during mobility, we demonstrate a comparative network performance to address the effect of WBAN speed at different hello intervals. The comparative analysis show, protocol implementation with a cross-layer approach outperforms the conventional protocol without MAC adaptations in terms of energy efficiency, network throughput, and a reduced end to end delay, by an average of 0.45%, 2.8%, and 13.7%, respectively.

Keywords Congestion control · Energy efficiency · Mobility · Routing · Wireless body area networks (WBAN)

1 Introduction

Evolution of the Internet of things (IoT) and smart health envisions the expanding commercialization of the biological sensors for health monitoring. Recently, wireless biological sensors positioned in, on, or off the human body remotely measures vital physiological signs for predictive health analysis (Kruse et al. 2017).

Communication between wireless biological sensors may use different wireless technologies, including IEEE 802.11, IEEE 802.15.3, IEEE 802.15.4, and IEEE 802.15.6 standards. The coordination of wireless biological sensors defines a wireless body area network (WBAN) whose evolving usage may shortly raise numerous quality of service (QoS) constraints.

The increasing number of WBAN users envisage the possibilities of multiple WBAN existence in a localized area. Under such circumstances, users in areas, including healthcare facilities, public libraries, shopping centres, and sports grounds, may face network performance impediments due to the rising competition for the scarce network resources. Inadequate resources affect network performance through packet collision, extreme energy consumption, delay, and degraded throughput.

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For contention-based channel access, collision happens whenever two or more devices are simultaneously assigned the same transmission channel. Therefore, high device density per unit area in a multiple WBAN scheme requires collision control mechanisms. Through the medium access control (MAC) mechanisms, WBAN devices control packet flow and collision resolution. So, in the IEEE 802.11 standard, conventional medium access control with distributed coordination function (MAC-DCF) uses carrier-sense multiple access with collision avoidance (CSMA-CA) mechanism for collision control. However, in MAC, before declaring collision, packet processing priority in the relay or destination node depends on the packet energy and its arrival time. Besides collision, the packet processing mechanism (e.g., four-way handshake) with energy dependency increases delay, congestion, and packet drop rate, mainly when processing larger frames in a limited node buffer capacity (Chang et al. 2006; He et al. 2017).

Since the coexistence of WBANs can exist when devices are in a stationary or mobile fashion, localized mobile multiple WBANs face frequent topology changes due to the changing speed, direction of movement, and position. Such dynamics in a random manner may impose an intermittent disconnection of links between peer devices, causing network instability and the varying power requirement. Also, frequent topology changes during WBAN movement and device socialization may lower the network throughput spurred by extreme delay due to a lengthy route establishment mechanism, packet collision, traffic fluctuations, and excessive control messages during route repair. These impediments raise network discordance and retransmission power requirements (Correa-Chica et al. 2017; Liu et al. 2017). Hence, when communicating sensitive data in a mobile scheme, frequent link disconnections, and higher packet collision possibilities need an immediate response.

Basically, a WBAN is considered as a composite of sensors within the body vicinity and is linked to other networks through a gateway. A gateway can be a master node that aggregates information from all the tagged source nodes. Therefore, in this article, we use a master node (coordinator) to represent WBAN position since nodes within WBAN have a minimum location variation (as a group) relative to that of the coordinator (Movassaghi et al. 2014).

Due to the prevailing resource constraints, multiple mobile WBAN with a localized existence in health monitoring applications call for improved network performance consideration. So, an improvement in QoS considers real-time network performance with assurance in throughput enhancement and packet collision reduction (Issaoui et al. 2017). Although, prioritization of the QoS performance indicators' improvement, e.g., throughput and energy efficiency, varies depending on the application requirement (Anand and Sethi 2017; Pathak et al. 2015).

Nevertheless, WBAN mobility and body-to-body (B2B) communication in densely populated areas is vulnerable to network interference, path loss, and link outage. Also, the heterogeneity in the data rate from different body organs increases the transmission power requirement, packet collision probabilities, and link dropouts. The increase in network resources competition and erroneous devices raises communication complexity in a mobile environment (Bhanumathi and Sangeetha 2017; Ghamari et al. 2016; Hussein et al. 2015; Mora et al. 2017; Shu et al. 2015).

For WBAN energy conservation, methods for link reliability and energy efficiency prefers short node transmission distance. The transmission distance depends on the random node distribution in a given topology. For example, the IEEE 802.15.6 WBAN standard is a low energy protocol designed, preferably for single-hop transmission. Whenever the transmission distance is beyond node transmission range, multihop routing can be deployed for energy-aware applications (Zhang et al. 2017). Therefore, the deployment of the multihop cooperative routing technique reduces the gap between routed nodes, which lowers the node transmission power requirement (Al-Mishmish et al. 2018; Yessad et al. 2018 Chen et al. 2017). However, besides multihop routing, in a mobile environment, the variation in WBAN speed affects the hand over mechanisms and hence the efficiency and other network performance indicators.

On the other hand, multiple WBAN coexistence and localization increase node socialization and network activities with a proportional proliferation in radio frequency (RF) radiation emission from network devices. Emitted RF radiations expose body tissues under the vicinity of radiation risks. Some of the radiation risks include rising body temperature, cell dysfunction, development of cancer cells, enzymatic disorder, and difficulties in the proper blood flow around the body (Bangash et al. 2014; Gil and Fernández-García 2017). So, for personal safety, serious mitigation measures must be considered when designing devices or network routing mechanisms.

In the future, fully commercialized WBAN devices such as textiles, wrist bands, and other wearables will be pervasively deployed for use. WBAN devices coexistence will shortly become a new normal. The existence of multiple WBAN in a dense localizes area comes with several performance hindrances due to inadequate network resources in a shared unlicensed spectrum, such as congestion, energy scarcity, link outages, and packet collision. These hindrances affect network performance indicators, including energy efficiency, network throughput, and may increase packet delay. In this view, the main objectives of this article are limited to mitigating challenges faced by WBAN when they coexist in dense, localized areas. The primary article focus, besides others, is to propose alternative techniques that will encounter degrading energy, throughput, and delay performances.

Therefore, the contribution of this work focus on the following areas:

1. Proposing an alternative packet routing mechanism. During mobility, WBAN in multiple existences will face topology changes that alter node transmission range. An alternative routing mechanism uses a linear fitness function, which takes into account the distribution of nodes in a topology, node residue energy, and specific heat absorption (SAR) for routing decision. We also describe the fitness function parameters, its effectiveness, and inclusion in the routing table.
2. Fitness function parameter analysis. We analyze the relationships between individual fitness function parameters to the overall network performance indicators of interest, i.e., energy efficiency, throughput, and delay.
3. We are proposing a simple cross-layer routing mechanism. Since packet congestion and delay remain as one of the biggest network challenges during mobility, we use a simple cross-layer routing mechanism in the MAC and hello-interval variation during movement to analyze its impact on the performance of the collocated multiple WBANs. Since, whenever there is a link disconnection, the network will try to repair dropped links, through the cross-layer routing mechanism, we also address the impact of hello messaging intervals to the network performance.

Presumption: In this work, we presume that all the WBANs in a multiple localized existence use the same set of rules.

The rest of this article is composed of the following sections: Sect. 2 summarizes the literature survey for collocated multiple WBAN existence, energy efficiency, and performance enhancement. Section 3 describe the proposed method. Section 4 describes the system model, simulation set up and results discussion. Section 5 concludes the article.

2 Literature review

WBAN uses miniaturized biological sensors characterized by a limited memory and battery capacity. Besides energy and memory scarcity, WBAN suffers from network issues, which comprise the link instabilities, interference, end to end delay, collision, and packet loss. Some of these glitches can be solved by using cross-layer mechanisms. Cross-layer routing involves various mechanisms in different layers, e.g., Network, link, or physical layers, to integrate several processes for efficient packet communication and network performance (Le and Moh 2015). The use of cross-layer routing allows cooperative multilayer response to communication challenges between neighbours by providing hybrid performance characteristics.

Besides, the evolving commercialization of WBAN devices draws researchers' attention to similar challenges in multiple WBAN existence schemes. Despite the limited signal transmission distance, it is complicated to meet the QoS requirement when different users come close to each other. The existence of multiple WBANs in a localized area compromise network performance due to competitive channel access and quality of service during transmission, e.g., in a densely populated area with WBAN users. In such cases, some of the research challenges are energy efficiency, interference mitigation, and channel quality enhancement for multiple WBAN existence in the PHY layer because higher interference raises retransmission energy demand and packet loss through collision (Dong and Smith 2012; Le and Moh 2015; Movassaghi et al. 2014; Sarra and Ezzedine 2016). Since each WBAN use independent coordinator, which may run under different transmission mechanism, devices in the multiple WBAN scenario may face complications when overhearing decisions from various sources. Methods including channel assignment schemes using other multiple access techniques such as time division multiple access (TDMA) have been applied to reduce interference by enhancing the signal to noise ratio (Dong and Smith 2012; Hwang et al. 2018; Sarra and Ezzedine 2016).

In the network layer, efficient route selection help to establish a stable link that ensures network energy efficiency and lifetime longevity despite the network existence in different schemes such as static, semi-dynamic, or dynamic. However, various data sources generate data at different rates with linear or nonlinear relationships raising different power requirements. In a complex and dynamic environment, data categorization leverage for extreme power demands. So, authors in Mohan et al. (2017) propose an energy efficient routing using an integrated linear and non-linear agent routing technique. The method classifies nonlinear emergency data from common data during packet forwarding where setting different transmission priorities minimize network load and, therefore, energy consumption and network delay.

In MAC, a four-way handshake includes sending a request to send (RTS), clear to send (CTS), data (DATA), and an acknowledgment (ACK) with an inter-frame duration after each frame (He et al. 2017). Depending on the MAC mechanism, packet processing may increase an end to end delay due to excessive queues in a limited network resource. In this view, topology changes in localized multiple mobile WBANs may increase packet delay even more. To avoid undue delays and energy consumption due to packet retransmission, authors in Khodabandeh et al. (2018) categorize packet forwarding priorities based on the hop count where packets from source nodes with a lower hop count are given higher precedence. The method assigns node activities based on the available load and transmission priority, which reduces the delaying of higher priority packets.

As the performance degradation is caused by different factors, in some applications, authors propose the use of multiparameter cost function to enhance WBAN performance since protocols with fewer routing decision components has never had the best performance (Kurian and Divya 2018; Le and Moh 2015). Some of the parameters used for routing decisions based on residue energy and the distance of the neighboring node from the source for the next-hop selection, where nodes falling below the set threshold, are omitted from the preferred route (Devi 2017). Researchers in Hu et al. (2016) considered the body position and posture with the transmission path loss as a function of residual energy and node distance from the master node where the transmission ability depends on the node visibility to neighbors or the destination node and the best channel selection criterion.

In WBAN, network energy is the fundamental performance indicator. To ensure energy efficiency, researchers used different techniques. Some of the methods include the use of inter slot time intervals between each transmission, which optimizes power utilization for multivariate data transmission, communication of data packets without using relay nodes, and interference mitigation in multiple WBAN schemes (Boujnah and Mars 2017; Hu et al. 2015, 2016; Le and Moh 2015). However, coexisting networks operating under the same spectrum interfere, causing connectivity issues (Qu et al. 2019). So, to enhance network performance, different methods have been used, such as parameter adjustment in the MAC, prioritization in channel assignment, and an end to end delay reduction (Anitha et al. 2018; Deepak and Babu 2018; Sarra and Ezzedine 2016).

Besides interference and energy efficiency, network throughput and an end to end delay face a higher degradation in multiple WBAN existence. Since in collocated WBANs, the packet collision probability is higher, and so is the packet loss and delay, which degrade throughput even further. Beyond the routing protocols, network congestion eventually results to a broader bandwidth requirement, link failure, demand for excessive retransmission energy, packet loss, and delay (Gawas et al. 2019). MAC adjustment has been applied in different works to improve network performance; in Mkongwa et al. (2019), authors illustrate MAC adjustment techniques to improve energy efficiency by reducing retransmission attempts, but also the contention window (CW) adaptation for performance enhancement. However, CW adjustment may not solve all the network problems alone, as pointed out in Gawas et al. (2019), authors indicate additional issues affecting network throughput, such as the hidden terminal, exposed nodes, and RTS / CTS induced problems due to MAC mechanisms. So, in a multiple WBAN scenario with a mobility scheme, the use of hybrid routing mechanisms and congestion control methods would leverage for WBAN performance enhancement.

3 Proposed work

This work's main objective is to establish a stable routing protocol and congestion control mechanisms to enhance the network energy efficiency, throughput, and delay in a multiple collocated WBAN scheme. Based on the literature review, WBANs in coexistence faces several performance issues. In a stationary fashion, the shared network resources increase channel access competition leading to the collision, link dropout, and congestion. Similarly, in a mobility scheme, transmission distance between WBANs varies depending on the direction of movement or speed and the network topology. Frequent topology changes raise additional requirements for transmission energy and packet routing adjustment. Due to link outage, excessive hello messaging during route repair increases communication constraints in a highly dynamic environment. Therefore, to mitigate the communication bottleneck, we focus our study in two separate subsections: firstly, we propose a routing mechanism that takes into account the routing decision considering factors such as the distance ratio to residue energy, link energy reliability, and radiation effects in addition to sequence number and hop count. Secondly, we propose the MAC mechanism adaptation for an end to end delay reduction and network throughput enhancement during congestion. Finally, we conduct a comparative analysis of the network performance before and after MAC modification during mobility.

3.1 Proposed routing protocol

In this article, the proposed routing mechanism use cooperative relaying and packet forwarding technique for a persistent link establishment. Since the direct packet transmission from the source to the destination consumes more energy, the use of a multihop packet relaying reduces the transmission power requirement. Typically, in a conventional reactive routing protocol, packet routing takes the shortest path by considering only the hop count and sequence number. However, in this work, we consider a random distribution of WBANs in a given localized area where, based on the WBAN position and distance from the central device, packet transmission energy requirement varies from one to another.

WBANs near the destination use lower transmission energy compared to the remote ones. Apart from the irregular transmission energy requirement due to the WBAN position, the link lifetime depends on the conserved energy during network operation. Therefore the duration within which packet transmission lasts in a given link highly relies on the link's stability, which fundamentally depends on its residue energy. Taking energy-distance relationships will leverage energy planning for a routing mechanism. Also, in a multiple WBAN existence, WBAN transceivers cumulatively radiate heat due to socialization, which may have health side effects to the users besides affecting circuit transients. Hence, the proposed routing protocol takes into consideration the radiation safety measures. In the proposed protocol, the specific absorption rate is set below the international commission on non-ionizing radiation protection (ICNIRP) standard limit (Gawas et al. 2019). In establishing a stable link that accounts for the energy requirement based on node distribution, link reliability, radiations, and the packet transmission distance between neighbours or the central device, we propose a fitness function that embodies all these factors when deciding the most effective route.

3.1.1 Normalized distance to residue energy ratio

WBAN position at every instant of time composes the network topology through which information is shared. In a cooperative routing scheme, the interaction between one WBAN to another depends on the separation distance between the source and its neighbors. The separation distance decides on the energy required for packet transmission. Usually, direct packet transmission to the central control unit suits WBANs with shorter transmission distance because they use low transmission energy (Al-Mishmish et al. 2018; Chen et al. 2017). For energy conservation, packet transmission by the remote devices uses a cooperative relaying mechanism. In a multiple WBAN scenario using cooperative routing, each WBAN can be used as a relay to its neighbors. In each network operation, the central device calculates the normalized distance ratio of the WBANs and updates the routing table for routing decision making. So, for WBAN inclusion in the forward route, the routing decision compares the normalized distance to the neighbors' residue energy ratio, besides other criteria. The lower normalized distance ratio shows WBAN is near the destination with higher residue energy giving qualification for direct transmission, whereas the larger ratio shows a remote WBAN requires cooperative relaying.

Referring the distance from the distant WBAN as the Euclidean distance of the furthermost WBAN (D_f) from the destination and the source WBAN distance (D_{xy}) as the Euclidean distance between the source WBAN and the target in each routine, the normalized Euclidean distance (N_d) is given as a ratio in Eq. 1.

$$N_d = \frac{Distant\ WBAN\ (D_f)}{Source\ WBAN\ distance(D_{xy})} \tag{1}$$

The distance to energy ratio is evaluated using Eq. 2, where E_r is the WBAN instant residue energy.

$$DE_{ratio} = \frac{N_d}{E_r} \tag{2}$$

For the given two points (s,k), the Euclidean distance between point s and k is evaluated as in Eq. 3.

$$D_{eucledian(\overline{SK})} = \sqrt{(x_k - x_s)^2 + (y_k - y_s)^2} \tag{3}$$

3.1.2 Link energy reliability

In multiple WBAN existence, the deterioration of the network performance results from packet collision, which raises packet retransmission requirements. Based on the packet retransmission mechanism, node buffers may be overwhelmed by the packets waiting for retransmission. Excessive packet queues in the node buffer cause congestion as a result of degraded network performance. The congested network faces energy inefficiency, link outage (durability), extreme network delay, and declining throughput. Since WBANs suffer from link durability, in this article, we examine the energy reliability of the WBAN by considering the energy consumption rate during network operation as a component in the fitness function. The relationship estimates the duration in which a respective link can persist. Our proposed routing decision considers relay's inclusion from among the neighbors by choosing a more energy reliable WBAN. The state of the WBAN in forwarding packets determines its energy consumption, besides packet frame size and WBAN distance from the destination. Similarly, WBAN position in a topology decides its usability during socialization and so the energy management.

In this work, we define reliable links based on energy as the amount of residue energy of the link's peer devices. If two devices have higher power than others, the link between them appears to have higher energy reliability. The higher the WBAN energy, the longer it can participate in packet forwarding and network performance improvement. So, the choice of the best route considers link reliability as in Eq. 4, where the authenticity of the link in cooperative routing is taken as a function of the instant and residue energy of the neighboring WBANs.

$$E_l = \frac{E_i}{E_i - E_r} \tag{4}$$

where E_i, E_r, and E_l are initial and residue WBAN energy and the link energy reliability, respectively.

3.1.3 Specific absorption rate (SAR)

In a busy environment with multiple localized WBANs, the interaction between users increases WBAN activities such as requesting routes to forward packets from a source device or disconnected links, transmission, and detection of data packets. Mostly WBANs consume more energy through transmission, detection, and a little during idle listening. During the active duration, WBAN's consumed energy is radiated as electromagnetic waves, which has a heating effect to the surroundings. Since WBAN devices are placed into contact with the body tissues, radiated thermal energy is then absorbed by the body tissues resulting to several side effects, including signal attenuation, path loss, and other biological risks. Therefore, SAR consideration in the routing decision gives assurance for health risks mitigation measures and link persistence as the signal attenuation can be minimized due to consistent signal energy. We evaluate the SAR ratio for inclusion in the fitness function using Eq. 5, as applied in Mkongwa et al. (2019).

$$SAR_{ratio} = \frac{SAR}{SAR_{lim}} \tag{5}$$

3.2 Relay selection scheme

In ensuring enhanced performance and energy conservation in a multihop communication scheme, network devices must carefully choose the packet forwarding route. The packet forwarding mechanism selection is guided by different techniques such as ad-hoc on-demand distance vector (AODV) routing. AODV is one of the reactive energy efficient routing protocols whose packet forwarding mechanism depends on the sequence number and the number of hops from the source to the destination device. Since the shortest path is preferred, the relay selection mechanism of a conventional AODV uses the shortest route by selecting the lowest number of hops between the source and the destination. For each network operation instant, the control device (coordinator) updates the routing table with the most current information about neighbour WBANs. Whenever a source WBAN is ready to forward its packets will check the two parameters in the updated routing table for route selection decision making.

Referring to Fig. 1, a source device requests to forward packets to the destination device where each node in the route to the destination will forward the routing request until the destination device is found. As the destination device has information about each node in the route through the forwarded information, it will respond by sending reverse route requests considering a route with the most current sequence number and the lowest number of relaying devices. When the source receives the destination's feedback, then the reverse route is now used as the most preferred route, and packet forwarding starts. In this case, Fig. 1 illustrates that route 2 is the best route for packet forwarding.

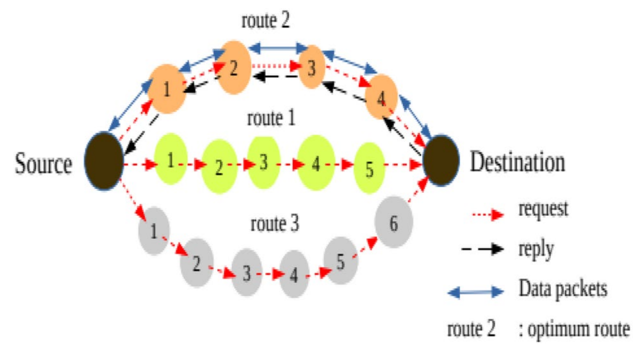

Fig. 1 An illustration of the optimum route selection mechanism based on the shortest hop count during the forward route request and reply

In the proposed protocol, apart from the sequence number and hop count, the relay selection mechanism considers energy balance based on WBAN distribution and network link stability, which subsequently optimizes network up-time. Therefore, selection criteria depend on two additional factors, WBAN remaining energy threshold and the maximum value of the fitness function at each network operation instant. The remaining energy threshold is the minimum energy a relay can use to send or receive at least one data packet. The preferred route selection decision considers the fundamental factors such as hop count and the sequence number in addition to DE_{ratio}, E_l, and SAR. So, each of the criteria is updated in every routing table update, before the route selection decision. The fitness function (fit) takes a linear combination of the normalized distance to energy ratio, link energy reliability, and SAR. For user safety reasons, SAR is limited far below 2.0 W/kg (ICNIRP standard) to keep the user extremely secure from radiation hazards. The fitness function relationship is governed by the linear relationship of the parametric values (considered as the weighting factors) whose adjustment vary network performance. The routing decision is then decided by the conventional characteristics, i.e., sequence number and the hop count, with an addition of the fitness function, which considers the additional factors for the best selection criteria.

The mathematical relationship in Eq. 6 gives the linear combination of the factors considered for cooperative-relay selection based on the normalized distance to energy ratio, link energy reliability, and the SAR.

$$fit = \alpha DE_{ratio} + \beta E_l + \gamma(1.6 - SAR_{ratio}) \tag{6}$$

where α, β, and γ are random parametric values with a cumulative sum of one every time they are used, i.e., $\alpha+\beta+\gamma=1$, the significance of varying α, β, and γ parameters demonstrate their impact to the general network performance. We put parametric (α, β, γ) values as regulators for the normalized distance to energy ratio estimation, link energy reliability stabilization, and thermal effect regulation, respectively. Selection of the parametric (α, β, γ) values bases on the random choice of arbitrary values where $\alpha, \beta, \gamma \leq 1$. The relationship between parametric values and the fundamental performance parameters of interest is given in the discussion of the results.

3.3 Functional description of the protocol

3.3.1 Reactive routing mechanism

In multiple WBAN scheme, packet forwarding is based on reactive routing techniques where a WBAN with packets to transmit will initiate routing requests by broadcasting hello messages. After initiating route request, sources will wait until it receives a route reply before starting packet forwarding. Devices between the destination and source will receive the route request. If they are not the destination, they will rebroadcast the request to its neighbours by retaining the routing information (update the routing table). When the destination is reached, it will use the routing information to send a route reply, which, when it arrives at the source, packet transmission begins. Any device that is not in the direction to the destination will soon drop the route after rebroadcasting the hello messages. In the proposed routing mechanism, during each routing update, the routing protocol computes parameters such as sequence number, hop count, distance to residue energy ratio, link energy reliability, SAR, and the fitness function value. A routing decision considers all the routing criteria such as hop count, sequence number, residue energy, and the fitness function's value, which is evaluated using Eq. 6. The fitness criteria for packet forwarding consider the fittest WBAN among neighbors must have the most current sequence number, the lowest hop count, residue energy above the threshold, and the maximum fitness function value. During route discovery, in a multiple WBAN scheme, the routing protocol selects the best neighbour based on the routing fitness decision criteria for packet forwarding, as illustrated in Fig. 1 and pseudo-code 1. WBANs in the most preferred route is said to be the most reliable, energy efficient with lower SAR.

Consider nodes in Fig. 1, where route 2 is considered as the optimum route. In a conventional routing mechanism, the qualification of route 2 as the optimum route is due to the fewer number of hops than any other route and the most current sequence number. However, for the proposed mechanism implemented in this article, for route 2 to be an optimum route, its devices must also have features, including enough residue energy and maximum fitness function. For simplicity, assuming each route in Fig. 1, exists as a single unit, qualification of route 2 implies: (sequence number, residue energy, fit)$_{route\ 2}$ > ((sequence number, residue energy, fit)$_{route\ 1}$ && (sequence number, residue energy, fit)$_{route\ 3}$); (hop count$_{route\ 2}$) < ((hop count$_{route\ 1}$) && (hop count$_{route\ 3}$)).

Pseudo-code 1: Reactive routing mechanism

```
1. Update neighbor list:
     Compute: hop count, sequence number, \
               DEratio, El, SAR, Er, fit;
    Update neighbor list in the routing table;
2. Route update:
    if ((sequence no= current) && (min.hop count)) {
       if ((Er ≥ Ethresh) && (fit ≥ Max.fit)) {
        update route;
          }
      else {
        delete route;
      send route request;
     go to 1;
       }
  }
3. Route repair:
     if (route up) {
       forward packets;
     }
   else {
      Repair route;
     go to 4;
     }
4. if (route repair time expire) {
     drop packets;
    drop route;
    go to 1;
     }
 }
5. End.
```

3.3.2 Congestion control mechanism in the MAC

The MAC mechanism based on IEEE 802.11 DCF uses CSMA-CA contention mechanism for channel access where packet forwarding deploys the four-way handshake. In the four-way handshake operation, different frames such as RTS, CTS, DATA, and ACK leverages for the collision-free packet forwarding process. However, the MAC DCF mechanism still faces an end to end delay challenges. In MAC before channel contention, all devices wait for the backoff period (BoF); this is the time a communication channel is occupied when one of the devices is transmitting. During BoF, all other devices remain in the idle state until the communication channel is free. When the BoF expires, contending devices will wait for the distributed interframe space (DIFS), which is the time interval between BoF and the beginning of the contention access period (CAP). DIFS helps for collision avoidance (CA). During CAP, devices send RTS packets and wait for the CTS after the channel allocation before DATA forwarding begins. In between each RTS, CTS, and DATA, there exists a short interframe space (SIFS), which also avoids collision between the handshaking packets and the hidden terminal problem. When transmitted DATA packets are successfully received, the destination sends an ACK acknowledging the source about transmission success. A source device accessing a channel will be assigned a network allocation vector (NAV) during which it will send packets without channel contention until NAV expires.

Similarly, all the other nodes which didn't have access to the channel during contention will defer until NAV expires before they contend for the second time. Also, devices which are not destination defer for a NAV duration even if they have data to transmit. During NAV, neighboring sources will not send RTS and CTS for channel access until the transmission time expires. This mechanism lowers the network throughput performance.

Besides reactive routing, the MAC mechanism causes extreme packet delay during WBAN mobility in a multiple WBAN scheme due to the higher possibility for recursive link disconnections. MAC faces several issues, including the hidden terminal, which is very common during movement, exposed node problem due to RTS/CTS_NAV, and channel errors, which contribute in the end to end delay (Gawas et al. 2019). Even so, in this article, we reduce the network delay time based on the packet processing mechanism and enhance network throughput during congestion by modifying the NAV duration where a node dynamically resumes RTS/CTS transmission. From the MAC DCF mechanism (refer Fig. 2), the successful frame transmission duration (SFT) of a given data frame is illustrated in Eq. 7.

$$SFT = RTS + SIFS + CTS + SIFS + DATA + SIFS + ACK \quad (7)$$

A congested network faces extreme packet queues (large data frame than it can handle), whereas the decision for dropping buffered packets depends on the energy level of the incoming packet compared to the packet being processed by the relay or receiving device apart from the interface

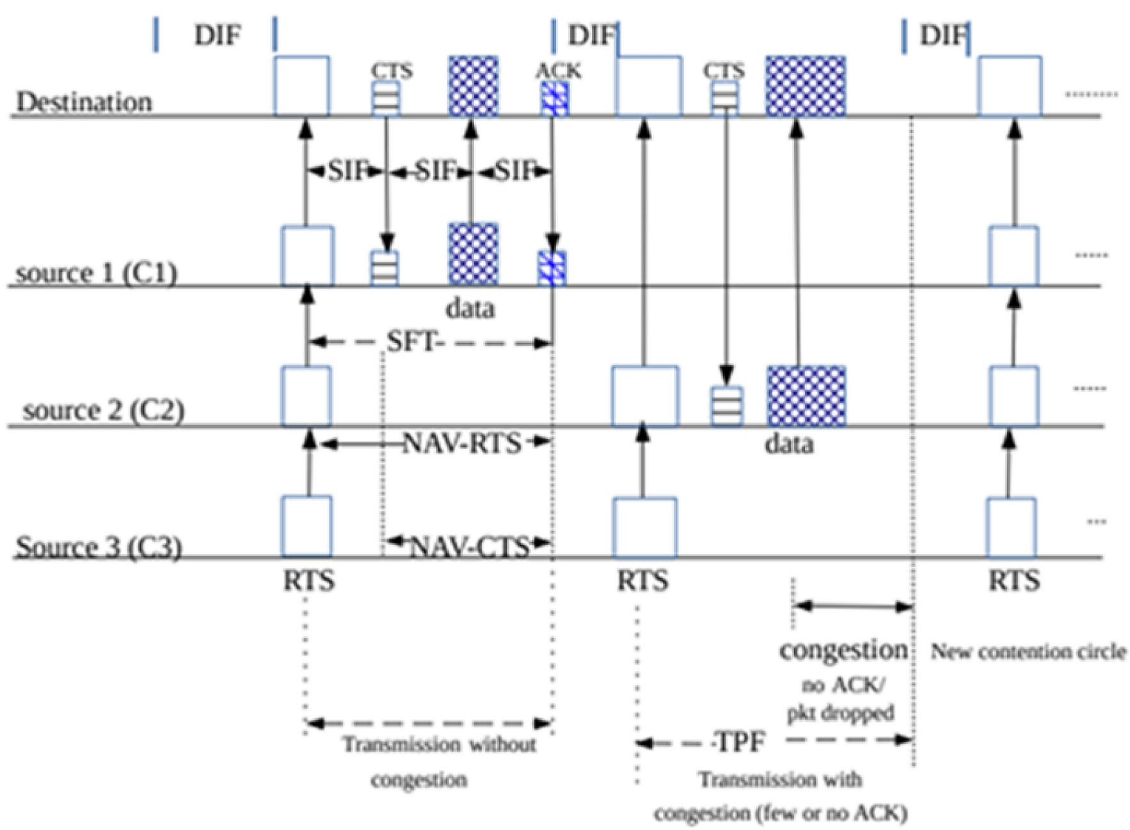

Fig. 2 An illustration of the RTS, CTS, NAV, and congestion scenarios during packet communication

queue (IfQ). During congestion, the packet processing duration increases network delay such that some of the packets are discarded only if the incoming packet has lower energy compared to the packet being processed or because of the extended processing period depending on the maximum allowable IfQ during synchronization. We denote the congestion duration as a delay Dc, which is the time duration, after which a packet is either dropped as collided one or delivered to the destination after processing. During congestion, the source receives fewer or no ACK packets since packet delivery is mainly unsuccessful. Therefore, the successful packet transmission is affected, and eventually, the packet forwarding efficiency. We define packet forwarding efficiency as a measure of the packets which successfully reach the destination despite the network delay. Generally, the time duration for the packet transmission until successful packet delivery is given by Eq. 8.

$$TPF = SFT + CT \tag{8}$$

where *TPF* total packet forwarding duration, *CT* congestion duration (Dc), *TPF* SFT given CT = 0.

The packet forwarding duration during congestion is given by Eq. 9.

$$TPF = RTS + SIFS + CTS + SIFS + DATA + SIFS + D_c + ACK \tag{9}$$

During congestion, a packet is either dropped as a collided packet or delivered to the destination after a delay time, D_c. Therefore, we define packet forwarding efficiency (PFE) based on Eqs. 7, 8, and 9, as illustrated in Eq. 10.

$$PFE = \frac{SFT}{SFT + CT} \tag{10}$$

PFE, in our case, delineates the network throughput enhancement criteria in the MAC during congestion. Equation 10 shows, if the network congestion is extreme, packet forwarding efficiency is highly degraded.

On the other hand, if the congestion duration (CT) is kept very low, the packet queue is adjusted, and the overall performance improves. The average packet forwarding efficiency (PFEAV) for a network of 'N' WBANs in a multiple WBAN system is given as in Eq. 11.

$$PFE_{AV} = \frac{1}{N}\sum_{i=0}^{N-1}\left(\frac{SFT_i}{SFT_i + CT_i}\right) \tag{11}$$

where integer i = 0, 1, 2, ……, N − 1.

Pseudo-code 2 demonstrates a simple congestion control mechanism.

```
P1= Power of the packet being processed at the receiving node.
P2= Power of the incoming packet to the receiving node.
1. if(idle) {
      source: Wait DIFS;
      send RTS;
      receive: CTS;
      forward packets;
   }
2. if(busy) {
     Neighbors: Assign RTS/CTS_NAV;
     defer for a BoF;
   }
3. if(congestion) {
      for (i=0; i<=N-1; i++ {
        If(P1>P2) {
          PFE:set low CT;
        }
        CT: expire;
        go to 1;
        }
     else {
       collision: discard packets;
         }
 else {
 go to 1;
 }
 }
 4. end
```

4 Simulation and results discussion

4.1 System model

The proposed system consists of multiple coexisting WBANs in a localized area. We set a network size of 300 m × 300 m in NS-2.35. The coordinator represents each WBAN since the coordinator position, by default, is the position of the WBAN. The multiple WBAN system consists of 11 randomly distributed WBANs and one central control unit. Each WBAN generates data (constant bit rate) at a rate of 12.5Kbps for a simulation time of 120 s. In the simulation, we use a packet routing protocol based on AODV and IEEE 802.11 MAC DCF. We assign each WBAN with an initial energy of 50 J and 100 J for the central control unit. We conduct simulation based on two distinct fashions: stationary network and a random motion mode at a speed of 1, 2, 3, and 5 ms^{-1} with hello-interval variation at 0.5, 1, 1.5, and 2 s in each simulation for mobility. Figure 3 gives an illustration of the multiple WBAN scheme in a localized area, and Fig. 4 shows the system architecture representing three collocated WBAN with mobility where at each time instant, the distance between one WBAN to another is given as d_{c13}, d_{c12}, and d_{c23}.

In Fig. 4, we consider only three localized WBANs for illustration. The coordinators C1, C2, and C3 are at a distance of d_{c12}, d_{c13}, and d_{c23}, as indicated in the diagram. When a coordinator changes position, it moves with its tagged nodes as a group (individual WBAN). During socialization, depending on the transmission distance and residue energy of the respective WBAN, they can communicate to one another. However, WBAN closeness may result to excessive radiation exposure to users and other network performance hindrances.

We execute the simulation of the proposed method in three different approaches. Firstly, we demonstrate the analysis of the parametric relationship of the fitness function parameters and their effects to the selected network performance indicators. Secondly, we implement the proposed routing algorithm by considering fixed and mobility fashions of the WBANs, where, due to recursive link disconnections during mobility, we vary the hello intervals in the route repair mechanism to examine its impact on the network performance. Finally, we deploy a cross-layer routing mechanism using a simple congestion control strategy for network performance enhancement.

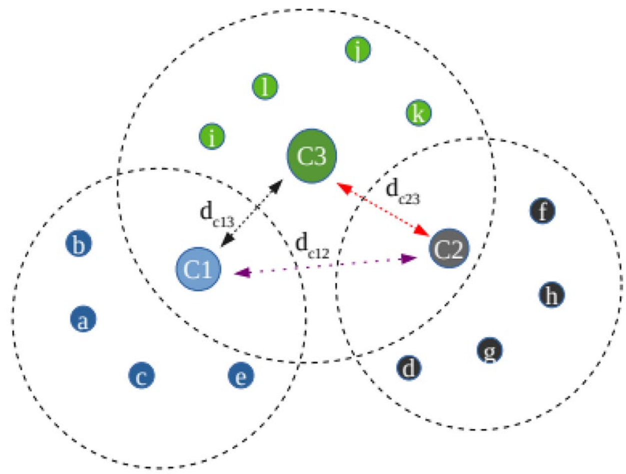

Fig. 4 An illustration of the system architecture showing WBAN (C1, C2, and C3) coexistence with mobility provision

4.2 Network performance parametric relationship

Since the route selection mechanism considers the existing and additional parameters for the routing decision, we have analyzed the impact of the proposed parameters in the fitness function related to the network performance. The proposed routing protocol's primary objective is to reduce energy consumption by establishing persistent links and provision of the lower SAR while enhancing network performance. So, the best selection of parametric values should provide the best network performance. However, in this article, the selection of the parametric values (regulators) is based on random selection. We randomly selected arbitrary parametric values conforming to $\alpha+\beta+\gamma=1$ in each simulation,

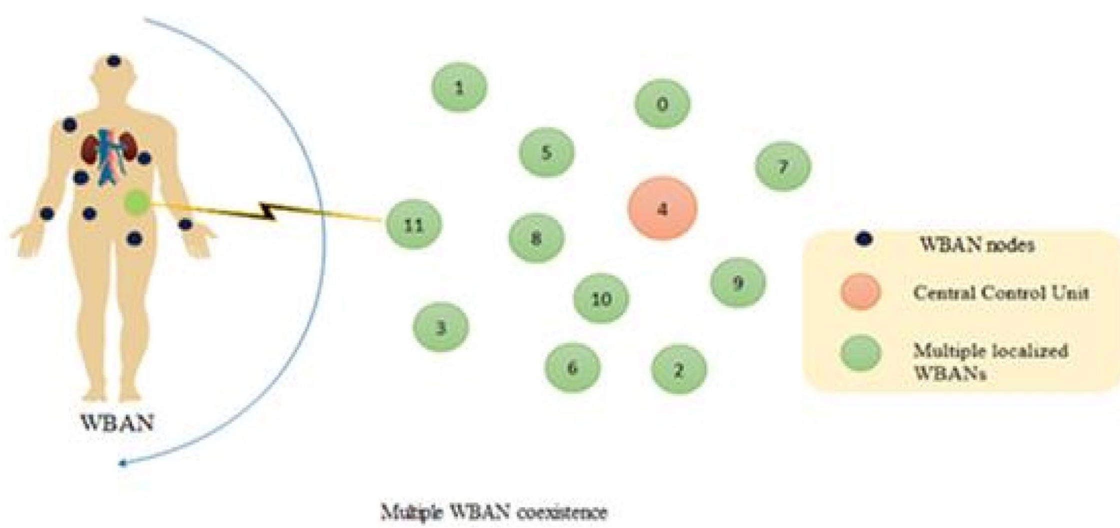

Fig. 3 An illustration of the multiple WBAN existence in a localized area where each coordinator represents an independent WBAN

where each parameter is an arbitrary value ranging between 0 and 1. Due to the nature of the application and the involved parameter, each parameter has a significant impact on the network performance, which need to be analyzed. Analysis of the simulation results focused on the parametric relationship with the network energy efficiency, throughput, and end to end delay.

4.2.1 Energy efficiency

The position of the WBAN in a given network topology determines the transmission energy requirement. Optimum route selection depends on the link energy efficiency where WBANs with enough residue energy get preference for inclusion in the packet forwarding route. We refer to energy efficiency as the maximum remaining network energy after the simulation time. Each parametric value has a significant impact on network energy efficiency and general network performance. To examine the parametric value impact for energy efficiency (α) regulation, we set link reliability (β = 0) and the SAR (γ = 0) to zero in the fitness function. Setting β = γ = 0 in Eq. 6, the fitness function gives normalized distance to energy ratio (α) relationship with the fitness value. Similarly, using Eq. 6, setting γ = α = 0, gives link reliability (β) relationship whereas setting α = β = 0, gives SAR (γ) relationship for energy efficiency with the fitness value. Considering the independent parameter relationship based on the assumption that other parameters are set to zero, the distance between the source and destination node affects the residue network energy, so the normalized distance to energy ratio depends on the instant WBAN energy and normalized distance ratio.

Similarly, the link reliability depends on the residue energy, so higher is the residue energy higher is the link energy reliability. For maximum fitness function, the value of β must also be significant. For independent parametric values, we obtain the following mathematical relations in Eqs. 12, 13, and 14 supporting simulation results from the fitness function in Eq. 6.

$$\ln(\alpha) = \ln(fit) - \ln(D_f) - [\ln(D_{xy}) + \ln(E_r)] \quad (12)$$

$$\ln(\beta) = \ln(fit) + \ln(E_i - E_r) - \ln(E_i) \quad (13)$$

$$\ln(\gamma) = \ln(fit) - \left[\ln(1.6) - \left(\ln(SAR) - \ln(SAR_{lim})\right)\right] \quad (14)$$

The network energy efficiency relationship based on the parametric values is illustrated in Fig. 5. For independent parameters, the simulation results show, the value of α and β relates inversely proportional to the residue network energy as we can refer to Eqs. 2 and 4 being one of the inputs to the fitness function, respectively. Plugging Eq. 2 in the fitness function and setting β = 0 and γ = 0 leads to Eq. 12, which gives the relationship between α and the residue energy based on the distance to energy ratio. Similarly, plugging Eq. 4 in the fitness function and setting α = 0, and γ = 0 leads to Eq. 13, which gives the parametric relationship between residue energy and link reliability (β). γ has a direct proportionality relationship with residue energy, referring to Eq. 5 as one of the components of the fitness function leading to Eq. 14. Setting α = 0 and β = 0 in the fitness function, we end up with Eq. 14, which gives a parametric relationship between γ and residue energy based on SAR.

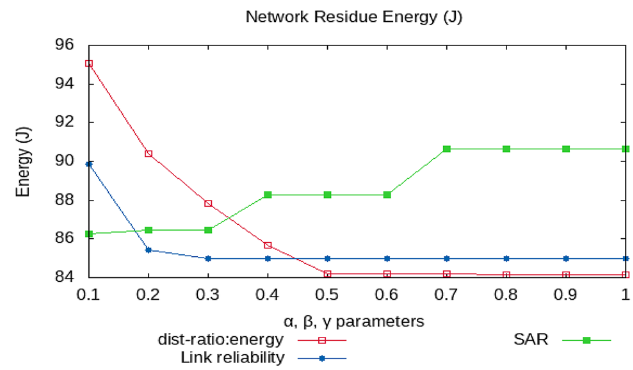

Fig. 5 Graphical parametric relationship of the fitness function parameters showing the variation of α, β, and γ with the network energy efficiency

4.2.2 Network throughput

The average throughput performance of the network depends on the existence of a reliable link between peer devices. The link reliability of the proposed algorithm considers link energy as a prime factor for route selection decisions. However, the position of the WBAN determines the transmission energy requirement and, therefore, energy efficiency strategy. In examining the parametric combination's impact on the routing decision and the network throughput optimization, link reliability plays a significant role. The fitness function is fundamentally related to the link reliability (β) as an independent parameter by setting α = γ = 0. However, α, and γ may influence general network performance, as well. Figure 6 illustrates the relationship between the fitness function parameters and network performance indicators. The parametric relationship show parameters, α, β, and γ have a superior throughput performance in the precedence order. The parametric values relationships, as illustrated in Fig. 6, indicate, the parametric contribution mainly depends on residue energy and link reliability, respectively. The modifiers for the normalized distance to residue energy ratio and link energy reliability have a more decisive influence compared to the SAR parameter. Simulation results illustrate that energy efficiency remains to be the most significant

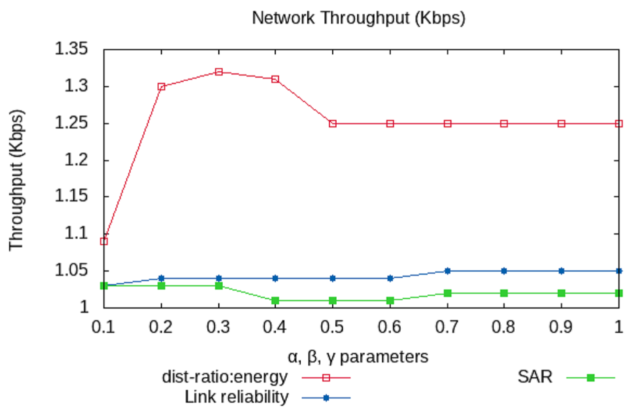

Fig. 6 Graphical parametric relationship of the fitness function parameters showing the variation of α, β, and γ with the network throughput

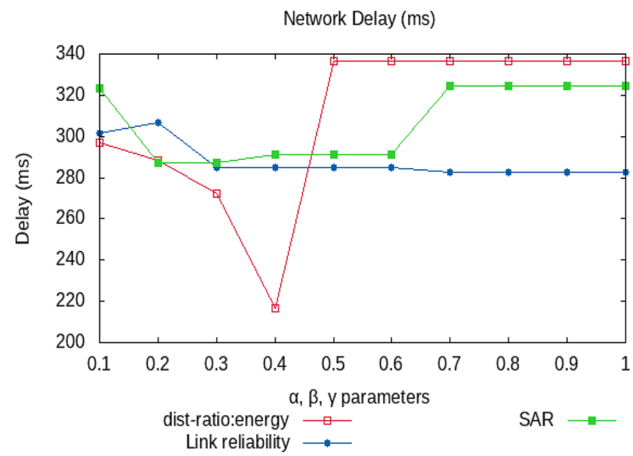

Fig. 7 Graphical parametric relationship of the fitness function parameters showing the variation of α, β, and γ with the network end to end delay

indicator. According to Fig. 6, network throughput performance is very high for $0.2 \leq \alpha < 0.5$, $\beta \geq 0.2$ and $0.1 \leq \gamma \leq 0.3$.

4.2.3 End to end delay

Complex routing protocols have complications when searching the optimum route. The choice of the routing mechanism may increase or lower end to end delay. For example, route selection based on the low transmission energy may involve multiple devices with a narrow transmission gap. Generally, a large number of devices in the route increase network overheads and, eventually, packet delay. Based on the proposed fitness function, link energy reliability provide more bearable delays only if stable links exist between devices. Similarly, the appropriately selected distance to energy ratio and SAR parameters have a lower end to end delay (e.g., $0.2 \leq (\alpha, \beta, \gamma) \leq 0.5$). However, the effect of the fitness function parameters shows, the best selection of the link energy reliability parameter gives lower network delay compared to SAR and distance to residue energy ratio, as demonstrated in Fig. 7.

4.3 Performance analysis of the proposed routing algorithm

The proposed algorithm takes into account the parametric combination of the fitness function parameters whose implementation mechanism is demonstrated in pseudo-code 1. In this case, we consider a stationary network. The fitness function linearly combines parameterized distance to energy ratio, link reliability, and SAR. Simulation results show the random selection of parametric values has a varying contribution to the overall network performance as they are interdependent to one another. Based on the illustrations in Figs. 5, 6, and 7, different parametric values have shown a significant contribution to network performance. Taking a combined relationship of the selected values in the regions with at least two outstanding combined outputs in α, β, and γ related to energy, throughput and delay give a higher probability of the overall network performance enhancement. The choice of the fitness function parameters may also depend on the performance indicator of interest. The best combination of the parametric values optimizes the routing decision that gives prominent performance output. Therefore, the optimum route selection ensures low energy consumption, thermal emission within standard limits, and reduced packet delay. Reduction in packet delay increases network throughput, and the low energy consumption ensures enhanced network lifetime, which contributes to the overall performance enhancement.

4.3.1 Energy efficiency

In ad-hoc wireless networks such as WBANs, energy efficiency is the fundamental factor for network designers. A properly designed system consumes minimum energy while delivering maximum performance. Several factors may contribute to the extreme energy demand, for example, the distance between communicating devices and the routing mechanism. So, additional criteria for the route selection decision leverages the energy requirement. However, the proposed protocol uses a fitness function parameter relationship that encompasses all the parameters at a time. As the fitness function parameters are interdependent, one parameter alone may not provide the best and stable performance, so taking the best combination of parametric values (e.g., α, β, $\gamma = 0.3, 0.695, 0.005$) optimizes routing decision and ensures an outstanding network energy efficiency. The combined parameters improve energy conservation, provides a reliable link, and keeps lower SAR so energy dissipation through heating is very minimal, allowing more energy conservation. Figure 8 demonstrates the energy efficiency performance of the network based on different combinations of parametric values.

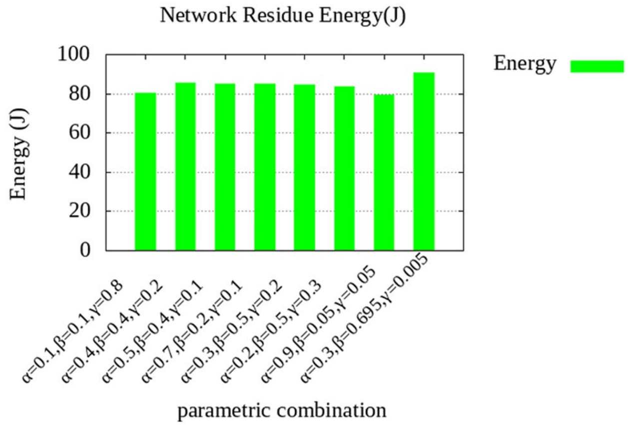

Fig. 8 Simulation results, demonstrating network performance based on the parametric combination of various fitness function parameters for energy efficiency

4.3.2 Network throughput

Persistent links give assurance for energy efficiency due to reduced hindrances during network operation, such as reducing packet loss due to link outage. Since, in this case, mobility is not enabled, the possibility of link outage is minimal due to fixed topology. There is no additional requirement of the transmission energy when the routing mechanism is steady. Also, stable routing lowers packet collision possibilities hence allowing more energy conservation and stable links. Stability in the link provides a conducive environment for packet flow and enhances network throughput. Simulation results in Fig. 9 show that, the energy efficient parametric combination in the fitness function (e.g., α, β, γ = 0.3, 0.695, 0.005 and α, β, γ = 0.7, 0.2, 0.1) have a notable network throughput performance. In this essence, properly selected parametric values improve network performance indicators.

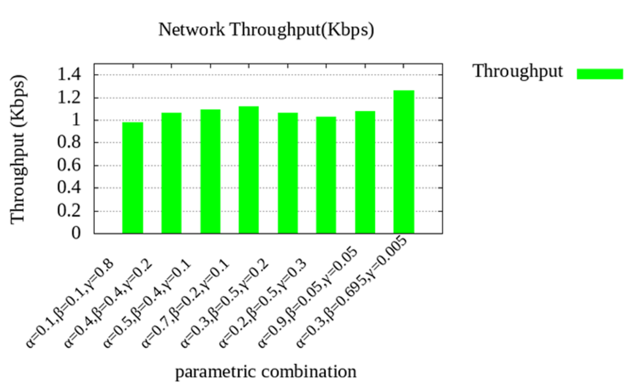

Fig. 9 Simulation results, demonstrating network performance based on the parametric combination of various fitness function parameters for network throughput

4.3.3 End to end delay

For WBANs used in vital health monitoring, a slight increment in network delay impede its performance and quality of service. Despite many factors that may cause network delay, such as the choice of the routing mechanism, extreme queues, and faulty network devices, the selection of the routing mechanism may leverage for the network delay possibilities when multiple criteria are used for the efficient route alternative. The appropriate selection of the fitness function parameters may lower network delay possibilities. The simulation results in Fig. 10 illustrates, different parametric combinations (e.g., α, β, γ = 0.2, 0.5, 0.3 and α, β, γ = 0.3, 0.695, 0.005) in the fitness function experience varying end to end delay. Figure 10 further illustrates some of the parametric combinations increases end to end delay (e.g., α, β, γ = 0.5, 0.4, 0.1), and some reduces end to end delay. Variation in network delay depends on the network dynamics, which may result to excessive flooding of the control messages due to recursive link discontinuities and packet collision.

4.4 Performance analysis for mobility and hello-interval variation

Although network performance faces extreme hindrance in a collocated multiple WBAN scheme, maintaining its best performance in such existence during mobility becomes more complicated. During mobility, WBANs experience frequent link discontinuities. So, retaining persistent links becomes a big challenge. For reactive routing protocols, a regular link disconnection raises more impeding issues, including rising demand for packet retransmission energy and extreme packet delay besides a collision. Such impediments affect network performance in terms of its throughput, energy efficiency, and the increase in the end to end delay.

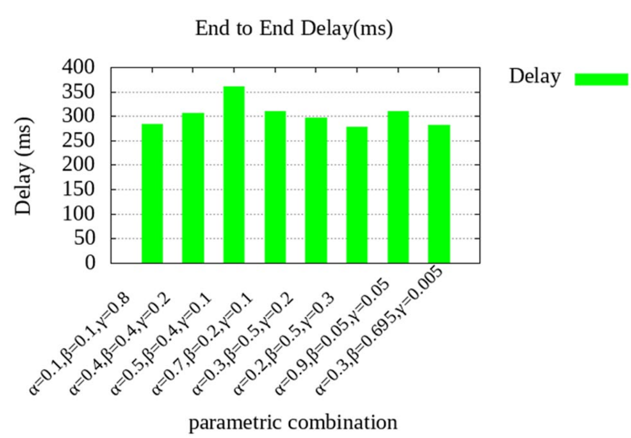

Fig. 10 Simulation results, demonstrating network performance based on the parametric combination of various fitness function parameters for end to end delay

On every link outage, the source sends hello packets searching for the optimum route. The flooding of hello packets in a network may cause unnecessary complications. So, in this article, we varied hello intervals to analyze the response of the proposed routing mechanism in a collocated multiple mobile WBAN scheme.

Considering random mobility, we varied the hello interval from 0.5 to 2 s in a range of 0.5 for the WBAN speed of 1, 2, 3, and 5 m/s. Each simulation result is taken as an average of 15 seeds of the same due to the random nature of the network performance in mobility. Simulation results were analyzed for energy efficiency, network throughput, and an end to end delay. Since we have many combinations of the parametric values during algorithm implementation, selection of the parameters used to analyze network performance during mobility based on the best performance in both energy efficiency, throughput, and low end to end delay analysis of the routing protocol when implemented in a stationary fashion. Referring to Figs. 8, 9, and 10 the parametric combination α, β, γ = 0.3, 0.695, 0.005 suffice the proposed criteria.

4.4.1 Energy efficiency

The random movement of the WBAN causes variation in the separation distance between one another. Varying separation distances raise different energy demands for packet transmission due to recursive link discontinuation. Similarly, the increasing WBAN speed may increase the separation distance abruptly. So, considering the route repair provision of the protocol, in this scenario setting small hello intervals will increase hello packet flooding hence the energy consumption. On the contrary, setting broader hello-interval guarantees for energy efficiency due to the lower number of control messages in the network infrastructure. However, network throughput performance may be distorted. Therefore, the selection of the hello interval must consider trade-offs between different performance indicators. Figure 11 illustrates the network residue energy characteristics for different hello intervals where the energy efficiency performance degrades as the WBAN speed increases from 1 m/s to 5 m/s. Also, as the hello interval widens from 0.5 s to 2 s, by average, the network residue energy increases accordingly since the frequency of the hello message broadcasts is reduced.

4.4.2 Network throughput

WBAN mobility causes frequent link discontinuation due to varying topology and distances between peer devices during network operation. Link outages increase transmission energy demands, which may result to extreme packet loss. Severe packet loss hinders network throughput. Also, during mobility, an increase in WBAN speed degrades network throughput performance. Similarly, as the hello interval widens beyond one second (1 s), the network throughput is further affected since the route creation for the broken links takes a longer time due to increased delay of the hello message broadcast. Therefore the route establishment mechanism in frequently disconnected links delays packet communication and hence network throughput performance. Figure 12 demonstrates the network throughput patterns for different hello intervals. When the hello interval is 0.5 s, the hello messaging frequency becomes very high. The possibilities of packet collision increase, and the network infrastructure are overwhelmed by the control messages that lower network throughput. Similarly, hello interval greater than 1 s reduces network throughput due to increasing delay for link establishment. However, at 1 m/s, the network throughput is higher than that at 5 m/s. therefore WBAN speed affects its throughput performance.

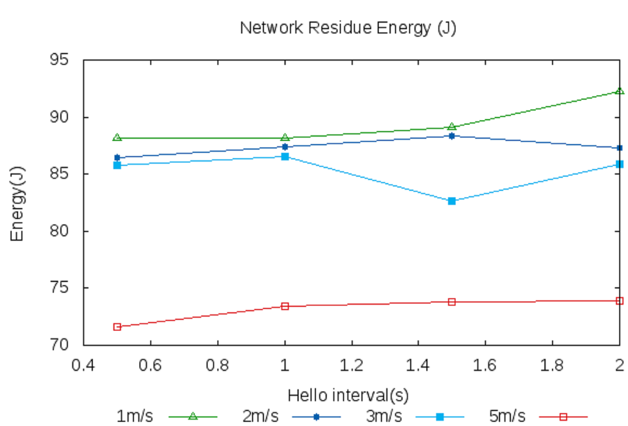

Fig. 11 Illustrating the effect of mobility and varying hello intervals to the multiple WBAN performance parameters on energy efficiency

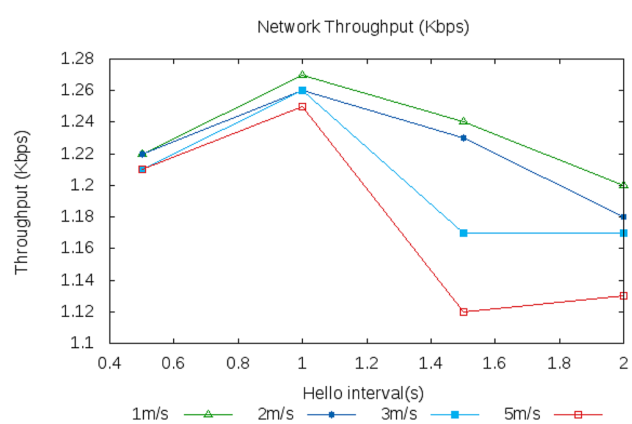

Fig. 12 Illustrating the effect of mobility and varying hello intervals to the multiple WBAN performance parameters on the network throughput

4.4.3 End to end delay

During mobility, the varying separation distance and the speed of the mobile devices increase link outage possibilities. Setting a very narrow hello interval (e.g., 0.5 s) in the MAC raises the likelihood of packet collision. The increasing packet flooding due to narrow hello-interval results in network congestion and hence the packet delivery delay. Similarly, the recursive routing requests and routing mechanisms may delay packet forwarding efficiency. The simulation results in Fig. 13 shows, the increase in a hello interval and the relative speed of the communicating devices increase the packet delay. With a hello interval of 0.5 s, the network infrastructure is overwhelmed by the control and data packets causing the collision. The transmission of the collided packets increases the delay. Also, the hello interval beyond 1 s indicates an increase in packet transmission delay due to the longer route establishment process. Higher mobility speed also increases link outage, whose reestablishment increases intricacy in the network operation, including higher delay. Therefore the appropriate selection of the hello interval will leverage network performance characteristics.

4.5 Congestion control and delay reduction

When there is an extreme queue in relays or destination devices, packet processing in a conventional MAC DCF protocol for packet forwarding or detection depends on its energy level or arrival time. Although the four-way handshake in the MAC mechanism contributes to the end to end delay possibilities, adjusting the MAC mechanism in line with the routing algorithm may reduce delay time for packet communication. When every source device forward packet to one device as a relay or destination, the target device becomes over flooded resulting to congestion. During congestion, the packet processing duration before the decision to discard as collided packets contribute to network delay. Reducing network congestion results in a lower transmission energy requirement, reduced packet queuing delay, and network throughput enhancement. The use of the routing mechanism in the network layer, together with the adaptive algorithm in the link-layer (MAC), enhances network performance metrics.

After MAC adjustment, while keeping the network in a stationary fashion, the simulation results showed improved network performance. Based on the parametric combinations, respective network performance using the proposed routing mechanism were compared with the cross-layer (CL) mechanism that adjoins routing with a congestion control mechanism. Figures 14, 15 and 16, illustrates the parametric

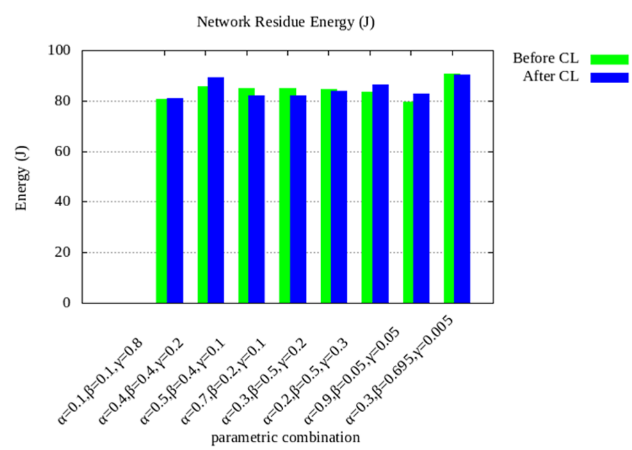

Fig. 14 Comparative analysis of the network performance before and after cross-layer (CL) adaptation based on the parametric combinations for energy efficiency

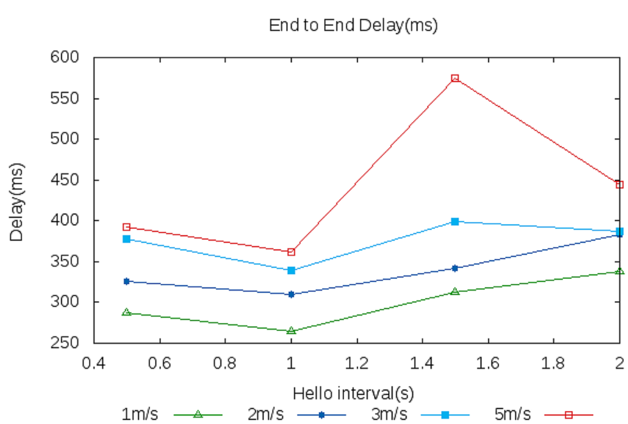

Fig. 13 Illustrating the effect of mobility and varying hello intervals to the multiple WBAN performance parameters on the end to end delay

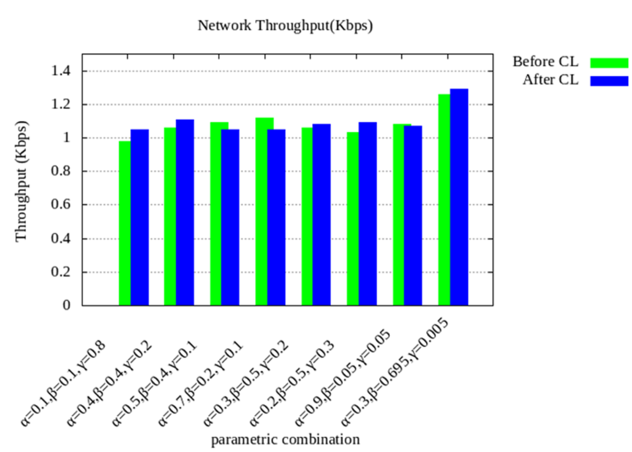

Fig. 15 Comparative analysis of the network performance before and after cross-layer (CL) adaptation based on the parametric combinations for network throughput

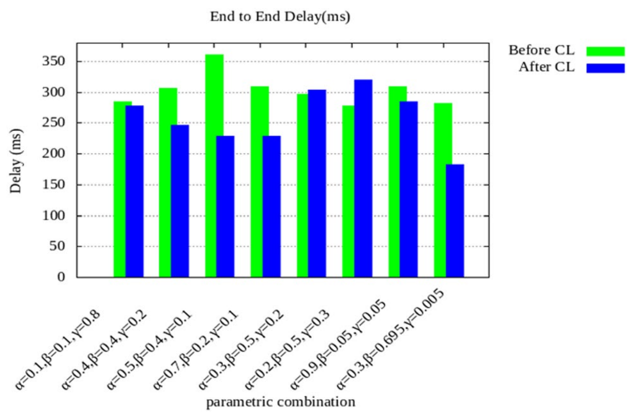

Fig. 16 Comparative analysis of the network performance before and after cross-layer (CL) adaptation based on the parametric combinations for end to end delay

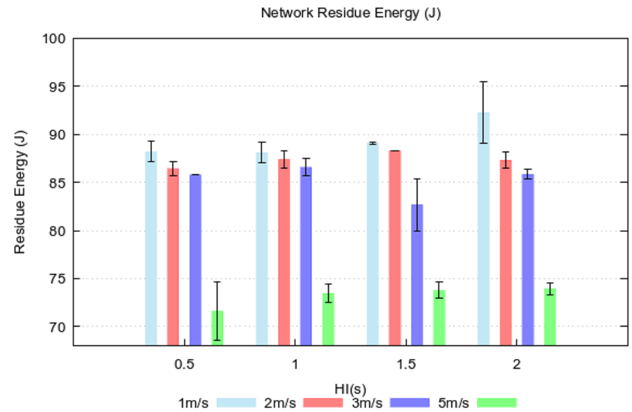

Fig. 17 Comparative analysis of the network performance in energy efficiency before and after cross-layer (CL) adaptation for different hello intervals during mobility

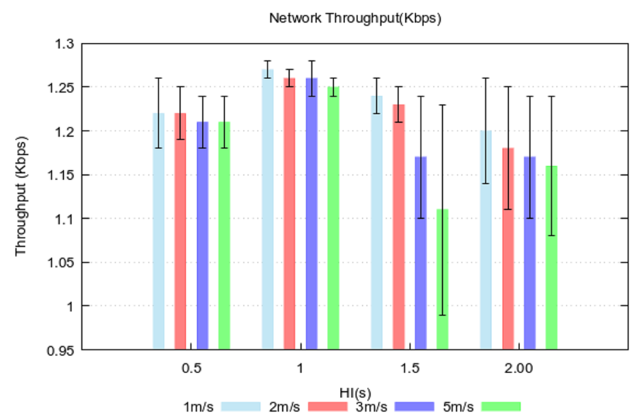

Fig. 18 Comparative analysis of the network performance in network throughput before and after cross-layer (CL) adaptation for different hello intervals during mobility

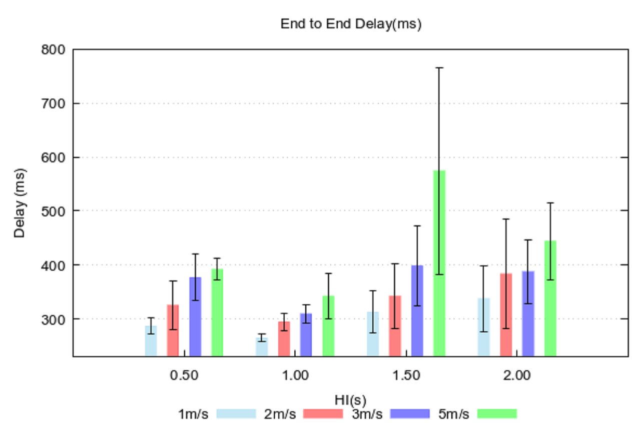

Fig. 19 Comparative analysis of the network performance in end to end delay before and after cross-layer (CL) adaptation for different hello intervals during mobility

comparative analysis of the network performance before and after MAC adaptation (CL). Simulation results show, performance enhancement in terms of energy efficiency for different parametric combinations (e.g., α, β, γ = 0.4, 0.4, 0.2 and α, β, γ = 0.2, 0.5, 0.3) as depicted in Fig. 14. Similarly, network throughput performance improved for different parametric combinations (e.g., α, β, γ = 0.3, 0.695, 0.005 and α, β, γ = 0.4, 0.4, 0.2) as illustrated in Fig. 15, and the reduction in the end to end packet delay (e.g., α, β, γ = 0.3, 0.695, 0.005 and α, β, γ = 0.5, 0.4, 0.1) as demonstrated in Fig. 16. Therefore, appropriate selection of the fitness function parameters for the routing mechanism can be embodied with other MAC mechanisms such as congestion control mechanisms to enhance network performance characteristics. Optimum route selection improves energy efficiency, network throughput, and reduces packet delay. However, the routing decision may increase packet flooding at the node interface due to the complex routing mechanisms resulting to congestion. Adjustment of the congestion duration reduces packet processing queues and possibilities of dropping packets as a result of queuing delay. Since dropped packets require retransmission, retransmission of packets may arise other requirements, such as additional transmission energy. So, the use of congestion control in line with the steady routing mechanism improves network performance.

On the other hand, during mobility, WBAN displacement and changing distance from one another increase network delay besides the increased demand for transmission energy and degraded throughput. After MAC adjustment, simulation results show, on average, there is a 13.3% decrease in the end to end delay, a 2.8% increase in network throughput, and a 0.45% increase in energy efficiency. Figures 17, 18, and 19 demonstrates the comparative analysis of the performance improvement in energy efficiency, network throughput, and the reduced end to end delay before and after MAC adjustment based on cross layer mechanisms, respectively, using error bars with 95% confidence interval. The error bars in Figs. 17, 18, and 19 indicate a significant improvement in residue energy, network throughput and end to end delay performance at different WBAN speeds. The congestion control mechanism has largely contributed in the end to end delay reduction, throughput improvement and energy efficiency in the precedence order as illustrated in their respective figures. Besides the performance enhancement, speed of the WBAN have largely affected the network performance. Figures 17, 18 and 19 indicates the inverse proportionality of the WBAN speed against network performance in energy efficiency, throughput and delay. Poor WBAN performance happens due to the link disconnections, excessive hello messaging during route repair, and packet collision due to frequently changing topology, that increases as the WBAN devices moves at higher speeds. The use of simple cross-layer routing has shown a significant contribution to congestion control. Adjusting the packet processing duration before a network device decides to drop packets has reduced packet queues in the buffers, packet processing delay, and increased the number of packets flowing in the network.

5 Conclusion

In this paper, we have designed a simple cross-layer routing for congestion control and performance enhancement in a multiple WBAN scheme. The proposed methods use cooperative adaptations in the network layer and the link layer. In the network layer, we have demonstrated that performance enhancement for multiple collocated WBANs, where the routing algorithm depends on the node distance to residue energy ratio, link energy reliability, and SAR. Since the routing mechanism is affected by the node transmission energy due to its distribution, and link reliability, all together must guarantee user safety due to the network devices' thermal emissions. However, the proposed routing mechanism could not give outstanding performance during mobility. During mobility, WBANs face recursive link disconnections due to frequent topology changes. As a result, routing repair and MAC mechanisms, flood control message broadcast into a limited network infrastructure, causing packet queuing, congestion and extreme delay. We analyzed the effect of varying hello-interval during route repair to the network energy efficiency, throughput, and packet delay. The analysis showed that the performance parameters are highly degraded when the hello interval is lower or higher than one second (1 s). We find that for different hello intervals at different WBAN speeds, simulation results followed a similar pattern where the increase in speed degraded network performance. In the link layer, we adjusted the IEEE 802.11 MAC-DCF mechanism for congestion control. We find that the use of the cooperative routing with additional routing decision criteria in the network layer and adaptation of the MAC in the link-layer improves further the network performance parameters such as energy efficiency (0.45%), network throughput (2.8%), and a reduced end to end delay (13.3%).

Author's contribution QL designed the research work and reviewed the article, KGM conducted simulations, results analysis, and preparation of the article, whereas CZ and SW proofread the article and revised the organization structure.

Funding This work was supported by the Key Laboratory of Advanced Marine Communication and Information Technology, Ministry of Industry and Information Technology, China.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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