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A Reliable Data Transmission Mechanism in Coexisting IEEE 802.15.4-Beacon Enabled Wireless Body Area Networks

Kefa G. Mkongwa[1,2] · **Chaozhu Zhang**[2,3] · **Qingling Liu**[2]

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Abstract
Advances in wireless sensor and internet technologies has rapidly increased the prevalence of remote health monitoring using wireless body area networks (WBAN). However, it turns out that WBAN pervasiveness draws attention to address the data transmission challenges. Due to the limited bandwidth in the industrial, scientific, and medical (ISM) band , WBAN performance degrades in parallel with the increasing number of active devices sharing the same network infrastructure. As a result, during carrier sense the increasing device density impedes the synchronization mechanism that raises packet collision probabilities in the transmission channel. In this view, access to the transmission channel for health care applications in coexisting WBANs is limited, and the transmission of aperiodic data becomes unreliable. Therefore, in this article, we propose performance improvement for coexisting WBANs through transmission prioritization and adaptive channel access mechanisms. We categorize user data into classes and implement transmission prioritization scheme that considers data category, device synchronization, dynamic clear channel assessment (DCCA), backoff range adaptation, and packet retransmission trials in stationary and mobile networks. The simulation results show the performance of the proposed model's carrier sense multiple access with collision avoidance (CSMA-CA) for collocated WBANs in terms of throughput, delay, and packet delivery ratio outperform the conventional IEEE 802.15.4 and the transmission scheme applied in Traffic Class Prioritization Medium Access Control (TCP-MAC) protocols.

Keywords Backoff and Clear channel assessment (CCA) · Medium access control (MAC) · Synchronization · Transmission reliability · Wireless body area networks (WBAN)

1 Introduction

Wireless body area networks (WBAN) has become a pervasive remote vital health monitoring in modern health care. WBANs comprise the coordinated battery-powered wireless biological sensors attached on, within, or off the monitored body organs. Biological sensors sense and transmit measured parameters to the remote health care units for diagnostic

✉ Kefa G. Mkongwa
ggkefa@gmail.com

Extended author information available on the last page of the article

purposes using various wireless technologies [1]. Monitored vital body conditions may include blood sugar, blood pressure, electrocardiography (ECG), or other physiological parameters. Due to the recent advances in technology and miniaturization of the electronic devices, WBAN sensors can easily be embedded in textiles and other materials. Embedded sensors are attached as a piece of cloth or other flexible wearable devices such as wrist bands [2]. Hence, the use of the WBAN technology is poised to increase shortly because devices are becoming more portable, affordable, and fashionable. However, WBAN operational effectiveness faces various challenges, such as the constrained channel access success probability during carrier sense which degrades its performance for normal and critical conditions.

The pervasiveness of the WBANs may lead to the collocation of users as a result of intensive mobility during walking, running, or any other form of social interaction. The collocation eventually raises conflicting access to the wireless channel and excessive energy consumption because of the number of contending devices per channel, packet collision, hidden terminal problem, and interference due to control signal overhearing [3]. Similarly, as the number of devices operating under the same frequency band increases, the network resources become scarce, so adaptive mechanisms need to be deployed [4]. Besides, WBAN mobility may cause path loss leading to link outage, disconnection from other tagged devices, and delay. Since IEEE 802.15.4 medium access control (MAC) standard was designed specifically for low data rate, short-distance communication, and energy efficient applications, its support for energy efficiency finds extensive application in WBAN. Even though, channel access mechanism in IEEE 802.15.4 MAC for industrial, scientific, and medical (ISM) application at 2.4 GHz faces several challenges when more than one active coordinator (user) exists in the same network or the number of devices joining the network increases [5].

In particular, carrier sense multiple access with collision avoidance (CSMA-CA) is widely used in the contention-based wireless channel access and is a fundamental mechanism for MAC operation in IEEE 802.15.4 [6]- [7]. During the contention access period (CAP), MAC communicates control messages and is responsible for channel assignment for random and periodic data through guaranteed time slots allocation (GTS). However, the CSMA-CA mechanism cannot guarantee successful data transmission when multiple devices join the network. Nevertheless, the performance of CSMA-CA during CAP is not very effective since the access to the transmission channel depends on the synchronization between the respective sink node (coordinator) and the personal area network coordinator (PANcord) in a multiple WBAN scheme. Therefore, the transmission slot allocation in multiple WBAN scenarios under the contention basis becomes even more complex besides other coexistence issues.

Due to the social interaction in a multiple WBAN scheme, the operation of the WBAN, either centralized or distributed may have several devices joining or leaving the network at any time instant. Therefore, under the coexistence scenario, WBANs need higher scalability and operability. So, static channel access mechanisms such as time division multiple access (TDMA) may not be the best choice for reliable connectivity [3–7]. Mitigation of the reliability challenges needs to consider adaptations in the MAC through backoff mechanism, or channel access optimization according to the network conditions. Some of the adaptations involve channel access through the scheduled transmission of the classified data with priority, traffic load consideration, association, dissociation, and backoff mechanisms [8–11]. However, most of the MAC adaptations consider single-hop stationary networks. Therefore, further findings on the performance optimization in networks involving mobility or multiple WBAN scheme need to be unfolded.

In this article, we propose and demonstrate network performance optimization criteria for multiple WBAN existence considering the access to the transmission channel using slotted CSMACA. The proposed channel allocation for the source nodes depends on the synchronization between the WBAN coordinator and the PANcord. Optimization of the channel accessibility eventually enhances network performance in terms of throughput, packet delivery ratio (PDR), and the end to end delay reduction.

The organization of the paper consists of the following subsections. Section 2, discusses the literature review. Section 3, discusses the channel access mechanism in multiple WBAN existence under IEEE 802.15.4 enabled WBANs. Section 4, gives the detailed proposed methods for backoff mechanism, prioritized channel access, and performance optimization criteria. The simulation and discussion of the simulation results are discussed in sect. 5, and the conclusion in sect. 6.

2 Literature Review

Efficient operation of the WBAN sensors has long been impeded by its physical size and the working environment besides other technical challenges. The advances in technology reduce challenges of the sensor form factor meanwhile increasing its operational performance. However, adaptations in the MAC mechanisms highly contributes to the efficient operation of the WBAN [12]- [13]. Since WBAN works under a licence free spectrum with limited support bandwidth, access to the transmission channel becomes a considerable challenge, especially in areas with crowded WBAN device users due to social interaction and mobility [14]. In dense WBAN networks, individual devices generates heterogeneous data and the packet transmission is aperiodic. Therefore, the increasing number of coexisting active devices increase contention when accessing the transmission channel. In this view, the performance of the coexisting devices may encounter performance impediments due to interference, beacon collision, packet collision, excessive energy consumption, and link dropouts [14]- [15].

On the consideration for energy efficiency, the IEEE 802.15.4 standard has energy management provision for tagged devices to stay active during transmission or sleep when they have nothing to transmit. Despite the standards' advantage on energy efficiency, the MAC may not efficiently handle the complex channel access mechanism when the number of active devices increase [16], [17]. Hence, the use of dynamic duty cycle alone cannot be considered as the solution to other network performance parameter apart from the energy efficiency.

During carrier sense, WBAN devices must discover each other in the network through beacon scanning and association with the coordinator before the beginning of the packet transmission. However, the device association depends on the free transmission channel availability. When the number of active devices increases, the longer association process delays channel access, and increase energy consumption due to node mobility or packet collision [18]. Hence, the authors in [5] propose a delay reduction mechanism by halting channel scanning soon after a node receives the beacon or reducing the value of the beacon order (BO). Although, lowering of the BO may increase association latency, and channel access delay, which affect other network performance indicators.

Apart from energy efficiency and a successful device association, the networks' connectivity in the multiple WBAN scheme depends on reliable communication links. Link reliability takes into account the quality of transceivers, quality of the received signals, interference, noises, operation frequency, packet loss, and other environmental factors [19]. In a multiple WBAN scheme, the link reliability weaknesses may jeopardize network performance parameters [20]. Since there is no specific standard for multiple WBAN existence, different methods applied in mitigating performance challenges of the conventional WBANs may also be adapted for multiple WBAN schemes with identical conditions. For example, authors in [21] reduce the size of the transmission frame by dividing large packet frames into small segments during transmission. Segmenting transmission frame reduces packet loss and the retransmission energy requirement in unreliable network links.

Correspondingly, deploying contention-free multiple access techniques such as TDMA, setting data priority criteria for transmission, or using hybrid channel access mechanisms may suffice for the network performance parameters, including throughput, delay, and PDR. Enabling of the transmission priority allows specific vital information to be communicated in the order of precedence from one another with very low or without contention. Transmission prioritization ensures reduced delay, energy consumption, and timely delivery of data to the destination. However, a conventional IEEE 802.15.4 MAC has no built-in traffic prioritization mechanism as in IEEE 802.15.6 MAC [10, 22]. Nevertheless, the IEEE 802.15.6 superframe flexibility allow adjustments to support prioritized transmission for periodic and aperiodic data [4].

For performance enhancement, data traffic can be categorized into different classes based on the data source or the retransmission strategy. For example, in [11], authors categorize data into different priority classes and transmits in distinct backoff periods during carrier sense mechanism. The use of distinct backoff periods reduces collisions. Whereas, the authors in [10], firstly, categorize data traffic into emergency, on-demand, and regular traffic in the order of transmission priority precedence for collision and delay reduction. Secondly, authors split the active part of the superframe into CAP1 for emergency and on-demand data transmission, and CAP2 for normal data transmission. The size of each CAP segment depends on the size of the traffic load. However, in CAP, the CSMA-CA can not entirely remove packet collision since the backoff period is very narrow. Hence, researchers in [23] decided to adjust the superframe to create additional time slots.

Some MAC protocols such as IEEE 802.15.4 allow packet retransmission under a specific threshold to increase transmission reliability. Therefore, the backoff size of the subsequent backoff period can be adaptively adjusted based on the statistical data of the immediate failed transmission to accommodate more retransmission packets in the subsequent carrier sense routines or by using a collision-aware mechanism [4, 24]- [25]. Though, the limited node buffer size creates excessive queues of the failed packets, which may impair channel access probability. Hence, authors in [26]- [27] propose methods for retransmission of the failed packets in the subsequent slot or adjustment of the size of the next backoff to accommodate dynamic queue size.

During contention, the number of nodes per WBAN and the number of coexisting WBANs in a multiple WBAN scheme may extremely affect the performance of the network. As the CSMA-CA capability may be overwhelmed, in the IEEE 802.15.4 standard, nodes may request the use of specific GTS for packet transmission from the coordinator [28]. GTS uses TDMA, which is a contention-free multiple access technique used for periodic data transmission. TDMA can be implemented in line with the prioritized packet transmission to enhance energy efficiency and time slot allocation for sensitive data [29]. However, TDMA alone does not suit effective channel utilization in a more dynamic network due to its static transmission slot assignment with little consideration of the buffer requirement for heterogeneous data [3, 20]. In this view, some researchers propose hybrid mechanisms by integrating CSMA-CA and TDMA to support the handling of the network dynamics due to the randomness of the transmission channel [30].

In a multiple WBAN existence, nodes face conflicting decisions made by different coordinators within their vicinity, channel access complications due to the increasing number of devices, or deep fading when channel overlaps upon sharing the same license-free ISM band [14]. Due to fading issues, authors in [19] propose the use of MAC-TDMA, where packet transmission considers the dynamic scheduling based on sleeping slot or node buffer. In this method, nodes are forced to sleep dynamically any time the channel fading is detected. Even though, node inactivity during fading raises buffer conflicts on the next time slot. So, at the beginning of each CAP, the collision rate increases. Hence, in the process of solving the deep fading problem, the possibility of distorting other performance parameters such as throughput and PDR increases.

Similarly, WBAN performance in the multiple WBAN scheme may be impeded by the signal overlap between neighbouring devices, signal to noise ratio, or the signal detection range of a node. Signal overlap affects access to the transmission channel during clear channel assessment (CCA) mechanism due to conflicting signals [13]. The identification of a compromised device may sometimes depend on the node's signal strength detection from its neighbouring devices in a stationary or mobile fashion. WBANs existing in a transmission range of the other can interfere, and ultimately the possibility for channel access diminishes. In a multiple WBAN scheme, interference can exist between: sensors within or from different WBANs, sensors and coordinator, or a coordinator and another coordinator. With Multiple WBAN existence, interference mitigation may involve detection of node power as a measure of separation distance beyond WBAN devices' carrier sense range. A node power with minimum signal interference to noise ratio (SINR) below the signal threshold indicates a compromised device. Compromised devices are barred from the transmission. Therefore, the priority for packet transmission based on the interference status is granted to the devices with higher SINR [30].

3 Channel Access Mechanism in Coexisting IEEE 802.15.4 Enabled WBAN

3.1 The IEEE 802.15.4 MAC Overview

IEEE 802.15.4 MAC as one of the wireless standards, supports low data rates, short-distance communication, and low energy applications such as WBAN. It is characterized by its frame structure where the duty cycle may vary by adjusting between node sleeping and active periods. The active period defines the superframe duration (SD) composed of the contention access period (CAP) and the contention-free period (CFP), refer Fig. 1. In CAP, source nodes use carrier sense for channel access (CSMA-CA). For data demanding specific transmission bandwidth, source nodes are assigned GTS slots in the CFP after sending explicit requests to the coordinator during CAP. IEEE 802.15.4 MAC standard has two operation modes; beacon (slotted CSMA-CA) and non-beacon enabled mode. On a beacon-enabled mode, nodes wait for the beacon signal before packet transmission and the alternating sleep and active durations help in energy conservation. Further, the standard defines two types of devices, reduced function device (RFD) mostly referred to end devices and the full functional devices (FFD), which can act as a coordinator and manage

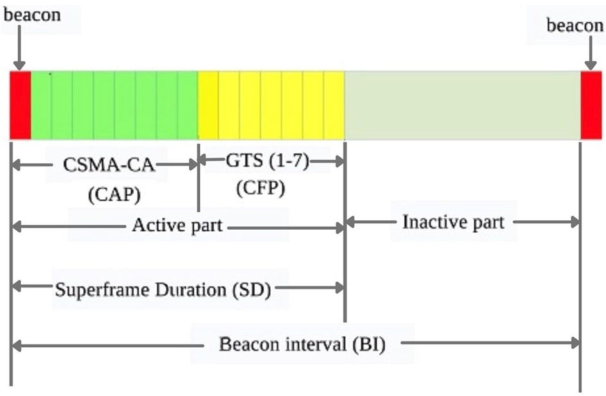


Fig. 1 IEEE 802.15.4 superframe structure

the operation of several RFDs. Device synchronization uses periodic beacon transmission, which defines the beginning and end of the superframe [13].

In a multiple WBAN scheme, several collocated WBANs may exist, as shown in Fig. 2. Each WBAN consists of its coordinator linked to the source nodes and the PANcord. WBANs may randomly move from one point to another, associate and dissociate with one another and the PANcord. In this article, the WBAN movement implies the movement of the coordinator with its linked sensors in one direction [15]. An illustration in Fig. 2 shows each WBAN consists of five sensors, including the coordinator, both linked to one PAN-cord. In multiple existences, performance issues arise when; the WBAN coordinators or sensors come into the vicinity of the in-range transmission of the other, the number of coexisting WBANs increases, or when the number of sensors in each WBAN increases [31].

When a source node of one WBAN exists in the transmission range of the coordinator of the other WBAN, it may result in an indirect beacon collision due to conflicting decisions by a different coordinator. Similarly, when the coordinator of one WBAN comes into a vicinity of the other, direct beacon collision happens as each FFD releases beacon for synchronization. In this view, access to the transmission channel becomes a big challenge, especially for aperiodic data, which depends on the logical mechanisms of the CSMA-CA.

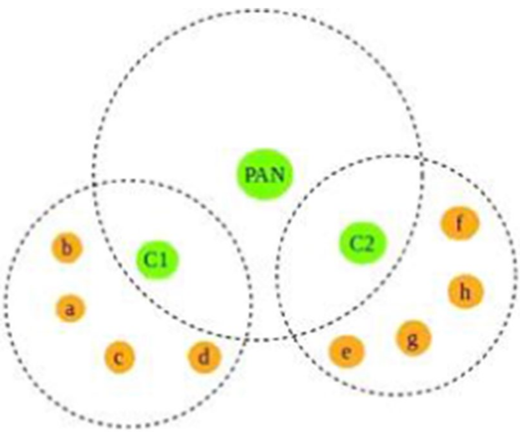


Fig. 2 Multiple WBAN existence where the PANcord is linked to each WBAN through coordinators C1 and C2

As a result, in this article, we propose to optimize data transmission reliability by enhancing the CAP performance of the IEEE 802.15.4 standard in a multiple WBAN scheme.

3.2 Channel Access Mechanism in the MAC

Fig. 2 shows the structure of the multiple WBAN scheme where source nodes are not in the transmission range of the PANcord. The synchronization between source nodes and the destination device depends on their respective coordinators' association with the PANcord. On this basis, packet communication is impeded by the channel access mechanism. Similarly, when the WBANs come very close to each other, nodes in WBAN-1 may overhear beacon signal from WBAN-2, and vice-versa, this setting may raise inter-WBAN interference issues. In this article, we only consider channel access mechanisms leaving aside the inter-WBAN interference issues where the multiple WBAN scheme configuration ensures no node comes into the transmission range of the other WBAN.

Under the multiple WBAN existence, access to the transmission channel depends on the condition in the PANcord. The properly synchronized coordinators with the PANcord assures packet transmission. In this case, to avoid beaconing conflicts, the coordinators' beacon interval must be similar to that of the PANcord. Therefore, a source node that synchronizes with the coordinator automatically synchronizes with the PANcord [31]. However, node synchronization alone may not be sufficient for a notable communication network's performance if the channel accessibility remains a significant challenge, especially for aperiodic data in an emergency scenario.

Since MAC is responsible for the wireless channel utilization through collision detection, time slot allocation, and nodes' transmission order, the MAC design plays a significant role in the performance of the WBAN under multiple WBAN existence [22]. Under the contention basis, nodes compete for channel access after receiving a beacon signal. The PANcord broadcasts a beacon signal at the same interval with the coordinators, and so nodes start carrier sensing, as shown in Fig. 3.

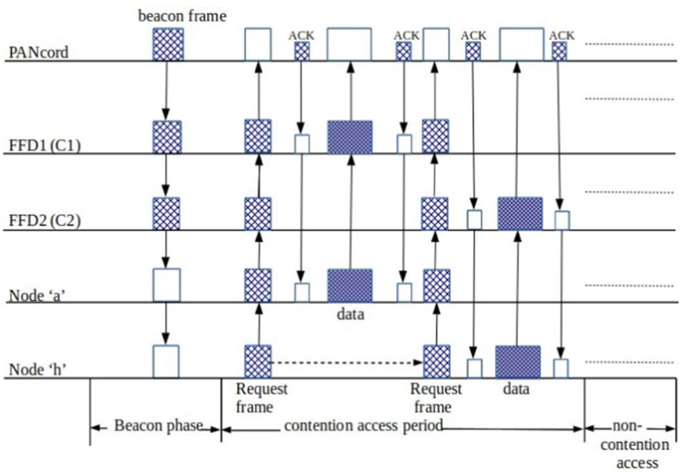


Fig. 3 Contention based channel access and packet flow for a slotted CSMA-CA in a Multiple WBAN scheme

Consider two FFDs; in this case, according to Fig. 2, we refer to $C1$ and $C2$ synchronizing with the PANcord as illustrated in Fig. 3. Nodes a and h content for the packet transmission in $C1$ and $C2$, respectively, where the transmission slot assignment by the PANcord depends on the contention outcome. In contention-based channel access, packet delay can be extreme and the network performance can be impaired through collision and transmission failure due to unsuccessful access to the transmission channel.

Data transmission may involve nodes wanting to transmit packets simultaneously, as shown in Fig. 3, and sometimes transmission may not involve node conflicts when each node transmits at different time intervals. On a contention basis, nodes compete for channel access using CSMA-CA due to its logical flexibility with simple scalability. In this view, the CSMA-CA mechanism is highly preferred to handle multi-network transmissions. However, there is no guarantee for reduced collision or packet delay during transmission due to the wireless media randomness. Since CSMA-CA cannot entirely eliminate losses through collision, different performance approaches such as time slot allocation, channel access control, active part interleaving, and power control using priority criteria can improve the quality of service (QoS) [7]. Based on the data transmission mechanism, the network performance responds accordingly while taking care of the impairing factors. Referring to Fig. 3, nodes a and h transmits packets to the PANcord through $C1$ and $C2$, respectively. As a result of the contention process, node a is acknowledged first and is assigned the transmission slot before node h, which has to wait until the next contention run time. On this basis, channel access in the IEEE 802.15.4 standard can be modelled to handle typical contention or prioritized access mechanisms for performance optimization [4, 11].

As discussed in the literature review in sect. 2, most priority-based modelling consider using backoff adaptations and categorizing the data traffic into different classes [12]. This article categorizes data into two main traffic classes; regular traffic for normal physiological conditions such as body temperature and emergency traffic for the most vital information, such as the heart rate. However, the packet transmission model falls under the channel access mechanism based on the dynamic transmission slot assignment according to its idleness.

4 Proposed Backoff and Channel Access Mechanism

This article aims to provide an alternative performance optimization criteria for contention-based channel access in a multiple WBAN scheme. As an extension of the work in [32], the proposed performance optimization criteria integrate adaptations in backoff mechanisms, channel accessibility, and priority-based transmission for the coexisting IEEE 802.15.4 enabled WBAN. The implementation of the proposed performance enhancement involves three steps. Firstly, since the backoff window is very narrow, we adjust the backoff period based on the number of packet retransmission trials. Secondly, as the complex channel access mechanism in a dynamic network may delay or drop data packets, we maximize the channel access possibility by modifying the clear channel assessment (CCA) mechanism. Thirdly, we propose prioritized traffic transmission where data traffic with higher priority is assigned a transmission channel by preceding others. The proposed enhancement criteria are described in the following subsections.

4.1 Backoff Adaptation Mechanism

In IEEE 802.15.4 MAC, the conventional backoff mechanism bases on the exponential backoff ($2^{BE} - 1$). The backoff range $[0, 2^{BE} - 1]$ defines the duration of the channel contention period, where the BE value ranges between the minimum to the maximum values (*macMinBE*, *aMaxBE*). The standard defines the *macMinBE* = 2 and *aMaxBE* = 5. For energy conservation, the standard allows adjustment of the Boolean battery low energy flag (BLE), which decides the span of BE values. When BLE = true, the *macMinBE* = 2 otherwise *macMinBE* = 3. When a transmitting node fails to access a channel in either of the backoff range, it increments the number of backoff exponent (*BE*) to a maximum value. However, when *BLE* is false, for $macMinBE \le BE \le aMaxBE$, the size of the conventional protocol's backoff period depends on the random number selected in the backoff range between; 0 – 7, 0 – 15, 0 – 31, 0 – 31, and 0 – 31. If the number of backoffs (NB) exceeds five, a node drops the packets and waits for the next carrier sense routine. Due to this backoff arrangement where each backoff window starts from zero, the collision probability increases as the possibility of assigning the same backoff number to more than one device increases.

To reduce collision probabilities through the random backoff number assignment, we propose distinct backoff windows for each backoff range in the proposed backoff mechanism. To further reduce excessive energy consumption for link lifetime maximization, we set the maximum number of backoffs to four. The proposed distinct backoff window ranges are; 0 – 7, 8 – 15, 16 – 23, and 24 – 31 [32]. Since the failed transmission may end up dropping packets, the standard protocol allows a maximum of three retransmission trials. However, in the proposed model, we extend the range of the backoff period when transmission failure happens in two consecutive retransmission trials. Extension of the backoff range aims to increase chances for channel access. Therefore, a tagged node selects a backoff period of the subsequent backoff based on the most current backoff's BE value as summarized in pseudocode 1 [32].

Algorithm 1 : Adaptive backoff mechanism

```
CW ← 2; NB ← 0; BE ← macMinBE;                    ▷ //initialize CW, NB, and BE
if channel == idle then
    wait for beacon
    perform CCA                                   ▷ //use CCA mechanism
else                                              ▷ //channel bussy
    if beacon==enabled then
        reset CW
        increment NB                              ▷ //NB= NB+1
        if NB≥ NBmax then
            busy                                  ▷ //channel access failed
        else                                      ▷ //back off again
            increment BE
            if BE>aMaxBE && aMaxFrameRetries>2 then
                set BE=[macMinBE (aMaxBE/aMaxRetries)+BE]   ▷ //resize-Bof
            else
                do nothing
            end if
        end if
    else
        wait for the beacon
    end if
end if
```

4.2 Dynamic Channel Access Mechanism

In a conventional beacon-enabled mode for IEEE 802.15.4 MAC, packet transmission starts after a source device receives a beacon and finds a free transmission slot. Detection of the free transmission channel uses the CCA mechanism for collision avoidance. After CCA, a tagged device allows data transmission only when the transmission channel is free. When the transmission channel is busy, the source nodes defer until the medium is free. Detection of the busy channel may use either of the following four modes: energy detection (ED) mode, where CCA reports busy state when the energy level of the channel is above the threshold; carrier sense (CS) mode where the busy channel is notified when a signal with similar modulation or spreading characteristics to that of the standard is detected; energy detection with carrier sense mode, which uses a combination of ED and CS mechanisms, or ALOHA mode, which reports only an idle channel [12].

The conventional standard requires two successive CCA stages during the idle channel detection. However, the time interval to complete the CCA process may affect throughput, node energy and delay, especially in a multiple WBAN scheme. To reduce energy consumption and enhance throughput performance, some authors in [8, 16, 32] and [33], proposes using a reduced number of CCA stages or segmenting the CCA mechanism by transmitting packets just after the end of the acknowledgment frame (ACK). Besides, the successive CCA is performed to avoid packet collision due to ACK or channel contention. However, in IEEE 802.15.4 MAC, ACK is optional.

Initially, the contention window (CW) counter is set to two ($CW = 2$), during CCA the CW decrements to zero by an interval of one ($CW = CW - 1$) before assigning the transmission slot when the channel is free. When CW =1 the CCA is in stage one and moves to stage two when the CW=0. In a conventional protocol, packet transmission takes place when CW=0 and the transmission slot is free. In this view, there is a chance that the transmission media is free just after the first stage CCA ($CW = 1$), but a tagged device defers until $CW = 0$. Instead of waiting for the two-stage CCA, in this article, we propose an alternative channel access mechanism by allowing nodes and their respective coordinators to transmit packets to the PANcord when the transmission slot is free in either CCA stages. The dynamic CCA mechanism increases source nodes' channel access probability, hence the network throughput. The proposed dynamic channel access mechanism is demonstrated in pseudocode 2.

Algorithm 2 :Dynamic CCA mechanism

```
if channel==idle then
    if beacon== enabled then
        CW − −                                        ▷ //decrement CW counter
        if CW == 1 and channel==idle then
            set CW = 0                                ▷ //transmit in CCA 1
        else
            if CW == 1 and channel !=idle then
                CW = CW − 1                           ▷ //decrement CW counter again
            else
                CW = 0
                if CW == 0 then
                    transmit packets                  ▷ //transmit in CCA 2
                else
                    reset CW                          ▷ //set CW=2
                    perform CCA again
                end if
            end if
        end if
    else
        beacon = not enabled
        wait                                          ▷ //wait for the beacon
    end if
else
    backoff again
end if
```

4.3 Transmission Prioritization Model

In this article, WBAN data are categorized by considering only two cases. On emergency or regular traffic settings. Transmission priority is in the order of the nature of the data traffic. Compared to regular traffic, emergency traffic is given higher transmission priority due to its time delay sensitivity in critical conditions. In the proposed model, packet transmission happens when a node has data to transmit and finds a free transmission channel during CCA. Therefore, when a source node with emergency traffic ($P1$) finds an idle transmission slot in the first stage CCA, it immediately contends for the transmission channel.

Similarly, in the second stage CCA, both emergency ($P1$) and regular traffic ($P2$) contend for the channel access. The channel accessibility is as defined in Table 1. Despite the traffic transmission prioritization, channel access at the PANcord is contention-based, since in a multiple WBAN scheme, emergency packets have equal transmission priority. However, the level of contention reduces due to different prioritization in the CCA stages. Reducing the contention level in the first CCA stage through priority-based transmission automatically improves network performance despite the randomness of the traffic sources from each WBAN in different scenarios.

Table 1 Description of the priority settings and channel accessibility of the data traffic during CCA

Priority	Type of data traffic	Transmision channel assignment
P1	Emergency traffic: e.g, heart rate, ECG	First and second stage CCA
P2	Regular traffic: e.g., Body temperature	Second stage CCA only

The flowchart in Fig. 4 demonstrates the implementation of the proposed transmission priority, backoff, and CCA mechanisms. The proposed performance optimization criteria adjoin the implementation of the proposed methods.

5 Simulations and Results Discussion

Simulation of the proposed protocol focused on the performance optimization during CAP. In this work, the CAP implements CSMA-CA mechanism as prescribed by the algorithm flow chart in Fig. 4 where, network performance optimization considers adaptations in the backoff mechanism, CCA, and priority-based transmission slot allocation for emergency and regular data traffic. The simulation results of the proposed algorithm were finally compared with the traffic class prioritization MAC (TCP-MAC) algorithm [11]. In TCP-MAC, the packet collision mitigation takes account of the backoff mechanism, which uses distinct backoff periods, whereas, the assignment of the transmission channel to the source nodes is prioritized based on the category of the network traffic. However, the assignment of the transmission channel in TCP-MAC does not involve CCA adaptation and packet retransmission model as applied in this article.

5.1 Simulation Setup

In this article, the designed multiple WBAN scheme consists of the PANcord and two WBANs. Each WBAN consists of the FFD and four source nodes, as shown in Fig. 2. Each network device was assigned 70 J of energy in NS-2.35. Different nodes in the intra-BAN

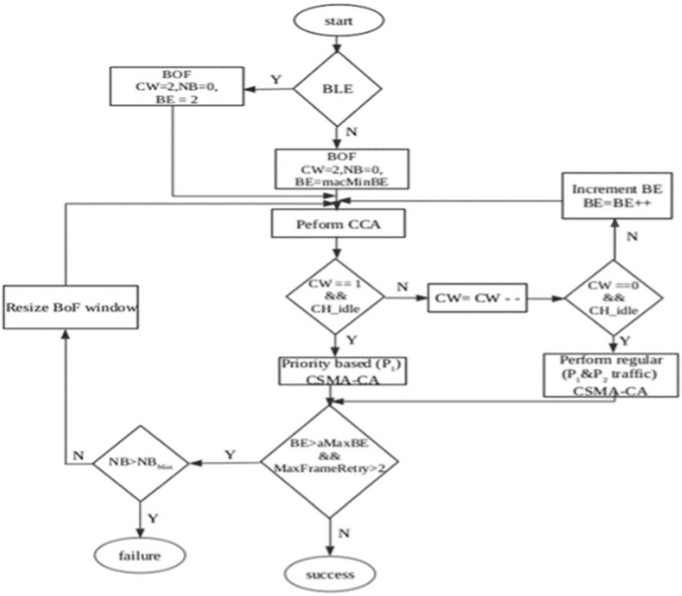


Fig. 4 Flow chart for the proposed mechanisms for backoff, CCA, and prioritized transmission. The flow chart summarizes the proposed mechanisms for performance optimization

were assigned different constant bit rates (CBR) to create a network with heterogeneous traffic supported in the 2.4 GHz band for ISM application. However, FFDs were assigned the same data rate to provide equal proportions of the data traffic contention from different sources to the PANcord.

The proposed model in this work have a reduced number of backoff periods (four backoffs) which lowers energy demand and enhance WBAN energy reliability. Since the conventional IEEE 802.15.4 MAC allows retransmission of the lost packets under a predefined threshold of three retries, in the proposed protocol, the backoff window is resized after every two consecutive retransmission retries to avoid excessive packet dropout. For beaconing conflict and delay avoidance, different BO and SO values were implemented to assess the effect of the beaconing mechanism in coexisting WBANs' communication delay. Hence, it turns out that when $BO = SO = 6$, our network model give significant performance. However, As the packet transmission delay in coexisting WBAN is subtle, during the simulation the WBAN delay performance with and without transmission prioritization is also analyzed. The simulation routine took 200 seconds, where the transmission of the CBR traffic started 20s after the PANcord and the FFDs are switched-on giving provision for linked devices synchronization. The PANcord and FFDs were started simultaneously to simplify beacon transmission routines and source nodes synchronization with the destination.

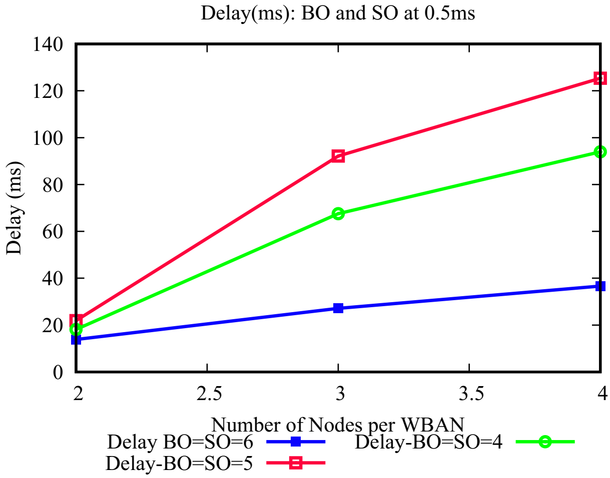
During the simulation, WBANs were allowed to move from one point to another and return to their original position. Besides, node mobility scheme were used to address the impact of movement and speed of the WBAN devices on the network performance in a multiple WBAN scheme at 0.5, 1, 2, and 3 m/s envisioning that involved entities may be in a state of walking slowly, faster, or running. Each simulation result is taken as an average of the ten best seeds recorded during model execution. Analysis of the simulation results focused on the essential network performance parameters such as throughput, PDR and the end to end delay as a result of the proposed model for the access to the transmission channel in a highly dynamic environment without interfering devices' transmission range to their tagged or neighbouring WBANs.

5.1.1 Analysis of the BO-SO Without Transmission Prioritization

For different BO and SO, WBAN delay performance in a multiple existence scheme depicts that the packet transmission delay depends on the synchronization intervals between RFDs and FFDs. However, the delay performance based on the BO and SO values is also contributed by the nature of the network topology and the number of the existing source devices per WBAN. Fig. 5 shows the coexisting WBAN delay performance for different BO, SO values at a WBAN speed of 0.5m/s, where when BO=SO=6 the simulation results show the lowest delay performance compared to other BO−SO combinations. Similarly, the transmission delay increases with the number of devices per WBAN.

Based on the $BO - SO$ performance, initial simulation of the proposed model involved the implementation of the proposed backoff, CCA and synchronization mechanisms without data categorization for transmission prioritization. It turns out that, the simulation of the proposed model without involving transmission prioritization outperforms the delay performance in TCP-MAC as well as that of the standard protocol when tested at a speed of 0.5 and 1m/s respectively. Therefore, the proposed backoff, CCA and device synchronization models have significant contribution to the WBAN performance enhancement in

Fig. 5 An illustrative comparison of the localized multiple WBAN delay performance for different BO and SO values at 0.5m/s



a rigorous multiple existence. For illustrations, the graphical analysis of the packet transmission delay performance at a $BO = SO = 6$ for different WBAN speeds is illustrated in Fig. 6.

5.2 Discussion of the Simulation Results with Transmission Prioritization

The primary research target were to illustrate performance enhancement of the WBAN in multiple collocated schemes using contention-based channel access during CAP. In particular the performance of a conventional single WBAN is affected by the increasing number of network devices due to the higher channel access competition during carrier sense (CS). As a result, performance optimization in a multiple WBAN environment is imperative. During CS, multiple WBAN scheme faces collision leading to the increasing communication delay and reduced throughput. Similarly, since most MAC mechanisms in

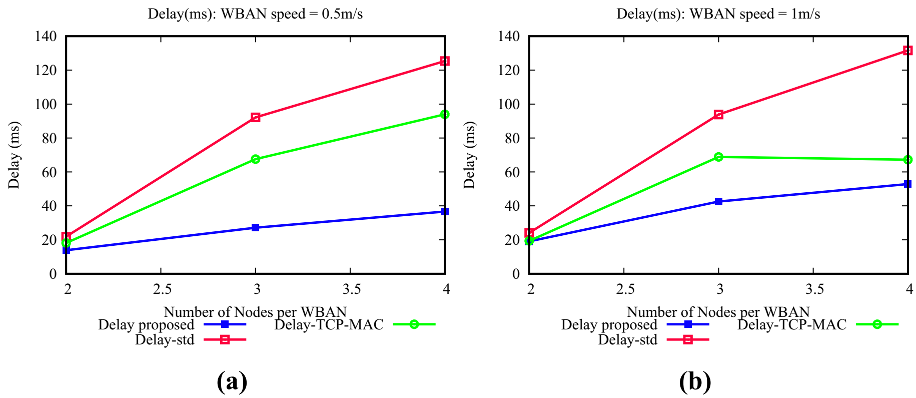


Fig. 6 An illustrative comparison of the packet transmission delay of the proposed model against the standard and TCP-MAC protocol at a WBAN speed of **a** 0.5 m/s and **b** 1m/s without transmission prioritization

IEEE 802.15.4 are fundamentally initiated during CAP, under multiple WBAN existence, it is essential to optimize the performance of the CSMA-CA. Therefore, the simulation of the proposed protocol involved analysing the simulation results based on throughput, PDR, and packet delay performance indicators. Besides assessing the effect of WBAN mobility, during the simulation, the number of source nodes per WBAN was varied from two to four under the same network conditions to address the effect of the node density to the coexisting WBAN performance.

5.2.1 Network Throughput

This article defines throughput as the number of packets flowing in the multiple WBAN scheme per second. Usually, the IEEE 802.15.4 MAC performance suffers when the number of devices joining the network increases. In this view, contention-based channel access mechanisms are significantly impaired in a multiple WBAN framework due to the long and complex synchronization algorithm between source nodes and the PANcord during the CAP. On this basis, the throughput performance of the network is degraded. Also, before transmission, source nodes must first confirm a free channel availability through the CCA mechanism. In the conventional CCA algorithm, confirmation of the free channel takes two CCA stages. However, there is no guarantee that the transmission channel will be free after every two CCA stages. So, the network throughput performance ultimately faces impediments when the number of coexisting WBANs increases besides delay irregularities. Since the increasing number of network devices impairs the channel access possibility under CSMA-CA, the implementation of different performance enhancement mechanisms in the proposed protocol reduces packet transmission impairments. Methods including using a distinct range of the backoff window and its resizing model during packet retransmission routine reduce collision chances. Similarly, setting packet transmission priority for categorized data traffic when the transmission channel is free in either stage of the CCA has further enhanced network throughput performance.

Comparing the network throughput performance of the proposed protocol with that of the conventional standard and the TCP-MAC shows throughput performance of the proposed algorithm outperforms the rest of the protocols as illustrated in Fig. 7. The simulation results demonstrates that during CS and retransmission routine, the fixed backoff window size in TCP-MAC limits packet retransmission efficiency, network scalability, and has proven to have poor performance in multiple WBAN scheme. The significance of the WBAN throughput performance enhancement by the proposed protocol is further demonstrated when the number of nodes per WBAN increases.

5.2.2 Packet Delivery Ratio (PDR)

Apart from the significant enhancement of the network throughput, the number of the successfully delivered packets may vary depending on the network conditions. Due to multiple network devices, the packet flow coordination is complex. Besides, the increasing number of nodes per WBAN complicates channel access and packet transmission mechanism. Hence, successful packet delivery to the PANcord can be impaired. In the proposed model, we consider PDR referring to the packets successfully delivered to the PANcord during CAP in a multiple WBAN scheme. Since the proposed channel access mechanisms take into account the collision reduction and prioritized packet transmission during regular transmission and in the retransmission mechanism by adjusting the backoff window size,

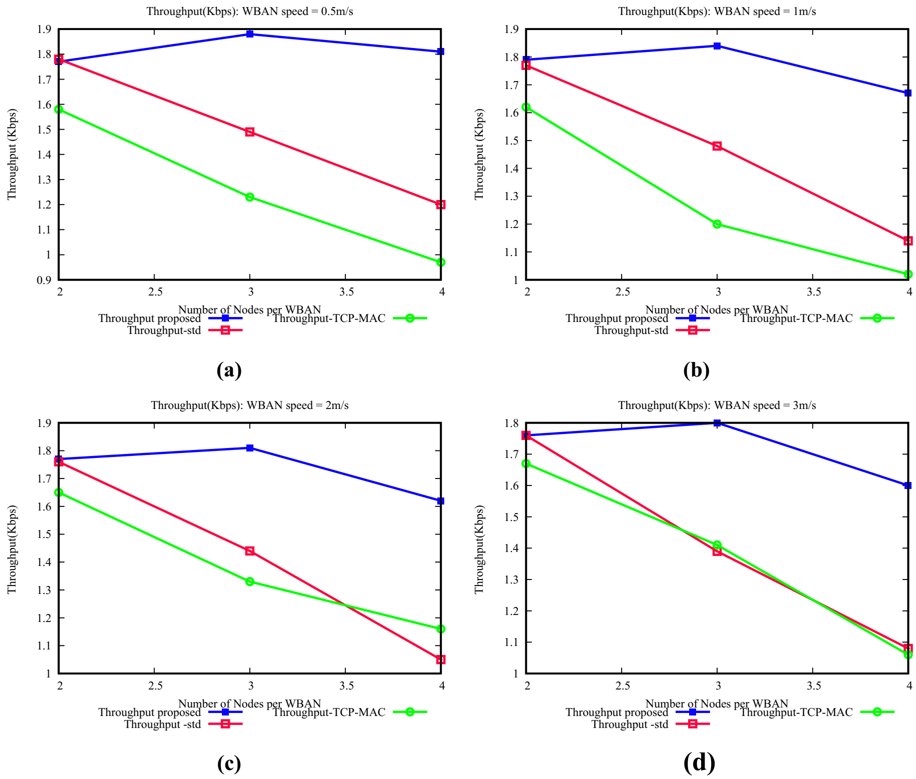


Fig. 7 An illustration of the performance comparison of the IEEE 802.15.4 enabled multiple WBAN coexistence with mobility. The comparison considers performance in network throughput for the standard protocol, TCP-MAC and the proposed mechanism at **a** 0.5 m/s, **b** 1 m/s, **c** 2 m/s, and **d** 3 m/s

reduced packet communication complexity increases delivery success. Also, the transmission channel assignment for data traffic in every slot of a free channel increases packet delivery without interruption. Hence from the simulation results, we find that the proposed model's PDR outperforms both the conventional protocol and the TCP-MAC. However, the PDR performance is affected by the number of nodes per WBAN, as illustrated in Fig. 8. With the increasing number of nodes in the corresponding WBAN, the PDR performance degrades gradually. Similarly, during mobility, as the speed of the WBAN increases, the packet delivery efficiency also decreases due to higher device dissociation as the WBAN changes position.

5.2.3 End to End Delay

This article considers end-to-end delay as the time taken by the transmitted data packets from the source nodes to the PANcord. In the multiple WBAN existence, several factors affect proper packet flow in the network resulting to packet delay. These factors include complex channel access and CCA mechanisms, beacon frequency in IEEE 802.15.4 enabled WBAN, beacon conflicts between neighbouring WBANs, packet collision,

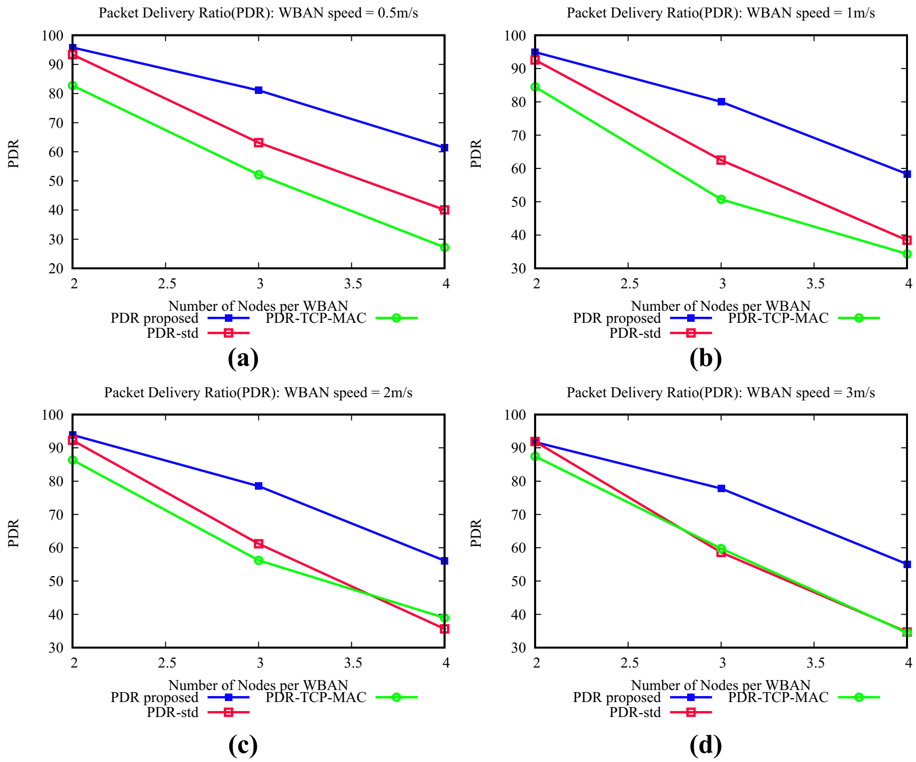


Fig. 8 An illustration of the performance comparison of the IEEE 802.15.4 enabled multiple WBAN coexistence with mobility. The comparison considers performance in PDR for the standard protocol, TCP-MAC and the proposed mechanism at **a** 0.5 m/s, **b** 1 m/s, **c** 2 m/s, and **d** 3 m/s

mobility, and external or internal interference. In the proposed model, end to end delay is minimized through collision reduction using distinct backoff periods, adjustment of the backoff window during packet retransmission retries, modification of the access to the transmission channel through the CCA mechanism, and the use of traffic priority during transmission. Based on the implementation of the proposed mechanisms, simulation results are as illustrated in Fig. 9. A graphical comparison shows the packet delay of the proposed channel access mechanism is lower than that of the conventional protocol and TCP-MAC. Also, an end to end delay performance of the TCP-MAC surpassed that of the conventional protocol. The simulation results indicate that the use of distinct backoff window sizes, CCA adaptation and prioritized transmission scheduling reduces network delay during CS. However, the simulation results in Fig. 9 further show packet delay in a multiple WBAN scheme is affected by the node density and device mobility. The packet delay increase when the mobility speed and the number of nodes per WBAN increase. The proportional increase in packet delay with the number of nodes indicates intra-BAN competition for channel access increases correspondingly with the number of nodes. In this view, in a multiple WBAN existence, packet delay becomes more severe due to a more complex transmission mechanism. However, the implementation of the proposed methods reduces performance impediments.

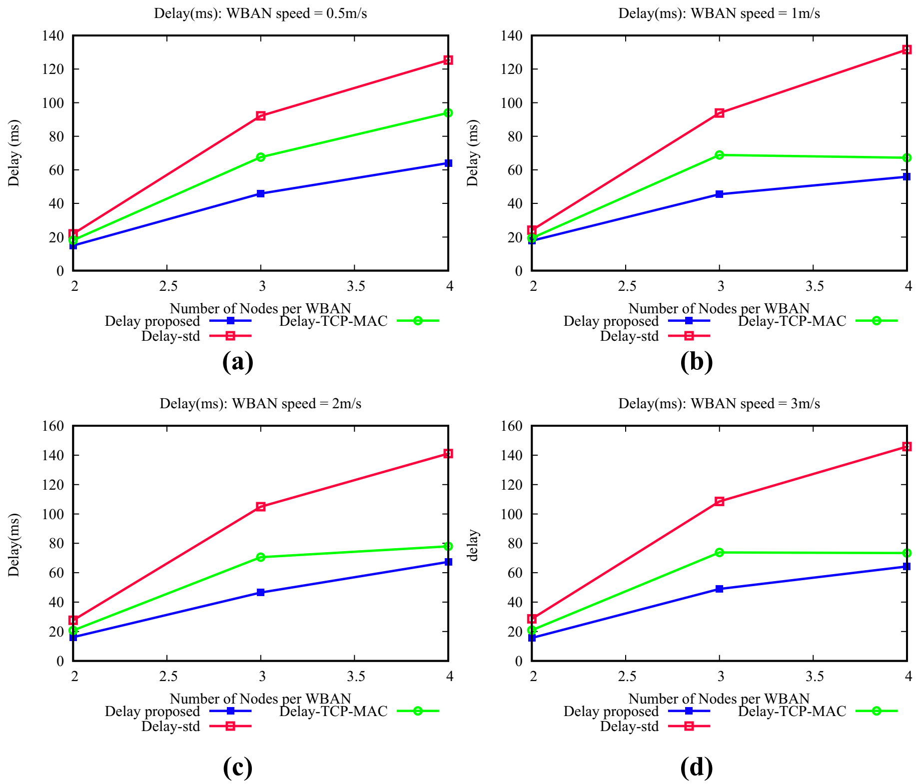


Fig. 9 An illustration of the performance comparison of the IEEE 802.15.4 enabled multiple WBAN coexistence with mobility. The comparison considers performance in end to end delay for the standard protocol, TCP-MAC and the proposed mechanism at **a** 0.5 m/s, **b** 1 m/s, **c** 2 m/s, and **d** 3 m/s

6 Conclusion

In this article, we have proposed a reliable data transmission mechanism for performance optimization in a multiple WBAN coexistence where, access to the transmission channel is based on the carrier sense mechanism during CAP for IEEE 802.15.4 enabled WBANs. Methods including the adjustment of the backoff window during the backoff period and on the packet retransmission routine, adaptation in the CCA and setting of the packet transmission based on the data traffic priority have been jointly applied for network performance enhancement. Besides, an appropriate synchronization of the source nodes and the PANcord by setting BO = SO to both coordinators and the PANcord has highly reduced association delay and leveraged packet transmission. In this paper, the WBAN performance optimization focused only on the CAP portion of the active part of the superframe. Since the CSMA-CA algorithm has features supporting adaptability and logical scalability with the increasing number of network devices, we modified the CSMA-CA mechanism to support performance optimization in multiple WBAN existence. The simulation results show the proposed mechanism for performance enhancement outperforms both the conventional protocol and TCP-MAC. However, performance optimization in this article did not take into account external interference. Thus, in the future, the integration of the proposed performance enhancement for channel access and packet transmission mechanisms with the external interference mitigation measures may provide the best solution in all operational aspects of the multiple WBAN scheme.

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Author Contributions KM: Conceptualization, software, experimentation, results analysis, writing–original draft preparation, review and editing; CZ: Results analysis and editing; QL: Results analysis, editing, and proof reading

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Data Availability The simulation data used to support the findings of this study are available from the corresponding author upon request

Declaration

Conflict of Interest The authors declare that there is no conflict of interest regarding the publication of this article

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Kefa G. Mkongwa received his BEng. Electronics and Communication Engineering from St. Joseph University of Engineering and Technology in Dar es salaam, Tanzania by 2009, in 2013 he received his MEng. degree in Signal and Information Processing from Tianjin University of Technology and Education in Tianjin, China, and a PhD degree in Information and Communication Engineering at Harbin Engineering University in Harbin, China by 2022. His current research interests, including Massive Internet of Things (MIoT), Wireless sensor networks, Wireless Body Area Networks (WBAN), MAC and PHY layers Performance Optimization, Microstrip patch antenna design and Intelligent Reflecting Surfaces (IRS) for 5 G and beyond communications.

Chaozhu Zhang received his B.S. degree in Electronics and Information Engineering, M.S. degreein Communications and Information systems and a Ph.D. degree in Signal and Information Processingfrom Harbin Engineering University in 1993, 2002 and 2006 respectively. Since 2009, he has been a Professor with the Harbin Engineering University. Currently, he is a Professorin the College of Electronics and Information Engineering, Qilu University of Technology (ShandongAcademy of Sciences), Shandong Province, China. Also, he is an academician of Aerospace Society anda member of the Institute of biomedical, Heilongjiang Province. His research interests include radar signalprocessing, biological signal processing, and communication engineering.

Qingling Liu received B.S and M.S degrees in signals and information processing from the collegeof information and Communication Engineering, Harbin Engineering University, Harbin, China in 2000and 2004 respectively. She completed her Ph.D. degree in Computer and Software Engineering, KumohNational Institute of Technology, Korea in 2012. Since 2018, she holds a deputy director of the institute in the College of Information and CommunicationEngineering. Her research interests include Wireless Network Technology, Internet Information Security,Artificial Intelligence, Information Technology, Routing in MANETs and Wireless Sensor Networks.

Authors and Affiliations

Kefa G. Mkongwa[1,2] · **Chaozhu Zhang**[2,3] · **Qingling Liu**[2]

Chaozhu Zhang
zhangchaozhu@hrbeu.edu.cn

Qingling Liu
liuqingling@hrbeu.edu.cn

1 Department of Electrical Engineering, Arusha Technical College, Junction of Moshi-Arusha and Nairobi Roads, PO.Box 296, Arusha, Tanzania

2 College of Information and Communication Engineering, Harbin Engineering University, Harbin 150001, Heilongjiang Province, China

3 Present Address: College of Electronics and Information Engineering, Qilu University of Technology, Shandong Academy of Sciences, Jinan 250353, Shandong Province, China