Enhancement of the Duty Cycle Cooperative Medium Access Control for Wireless Body Area Networks

Dalal Hammood
*Universiti Malaysia Perlis*

Hasliza Rahim
*Universiti Malaysia Perlis*

R Ahmad
*Universiti Sultan Zainal Abidin*

Ahmed Alkhayyat
*The Islamic University*

Mohammad Salleh
*State of Johor Department of Environment*

See next page for additional authors

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Authors
Dalal Hammood, Hasliza Rahim, R Ahmad, Ahmed Alkhayyat, Mohammad Salleh, Mohd Fareq Abdul Malek, Muzammil Jusoh, and Qammer Abbasi
Enhancement of the Duty Cycle Cooperative Medium Access Control for Wireless Body Area Networks

DALAL ABDULMOHSIN HAMMOOD1, HASLIZA A RAHIM1, (Member, IEEE), R. BADLISHAH AHMAD2, (Senior Member, IEEE), AHMED ALKHAYYAT3, (Member, IEEE), MOHAMMAD EZANNI MAT SALLEH4, MOHAMEDFAREQ ABDULMALEK5, (Member, IEEE), MUZAMMIL JUSOH1, (Member, IEEE), AND QAMMER H. ABBASI6, (Senior Member, IEEE)

1Bioelectromagnetics Research Group, School of Computer and Communication Engineering, Universiti Malaysia Perlis, Kampus Pauh Putra, Perlis 02600, Malaysia
2Faculty of Informatics and Computing, Universiti Sultan Zainal Abidin (UniSZA), Gong Badak Campus, Kuala Nerus 21300, Malaysia
3Department of Computer Technical Engineering, College of Technical Engineering, Islamic University, Najaf 54001, Iraq
4State of Johor Department of Environment, Johor Bahru 81300, Malaysia
5Faculty of Engineering and Information Sciences, University of Wollongong in Dubai, Dubai 20183, United Arab Emirates
6School of Engineering, University of Glasgow, Glasgow G128QQ, U.K.

Corresponding author: Hasliza A Rahim (haslizarahim@unimap.edu.my)

ABSTRACT This paper presents a novel energy-efficient and reliable connection to enhance the transmission of data over a shared medium for wireless body area networks (WBAN). We propose a novel protocol of two master nodes-based cooperative protocol. In the proposed protocol, two master nodes were considered, that is, the belt master node and the outer body master node. The master nodes work cooperatively to avoid the retransmission process by sensors due to fading and collision, reducing the bit error rate (BER), which results in a reduction of the duty cycle and average transmission power. In addition, we have also presented a mathematical model of the duty cycle with the proposed protocol for the WBAN. The results show that the proposed cooperative protocol reduced the BER by a factor of 4. The average transmission power is reduced by a factor of 0.21 and this shows the potential of the proposed technique to be used in future wearable wireless sensors and systems.

INDEX TERMS Wireless body area network, cooperative communication, duty cycle, bit error rate, average transmission power, energy efficiency.

I. INTRODUCTION

WBAN are communication networks of sensors (and/or actuators) placed on, inside, or perhaps around the body that represent a new generation of personal area networks and present different implementation challenges [1]–[6]. Sensors of WBAN are small, and they are embedded with a finite source, which is not the case for traditional wireless sensor networks (WSN). Finite batteries limit the energy available for the use of the sensor nodes in sensing, processing, storing, and sending data, and this directly affects the overall energy efficiency, the network’s lifetime, the transmission rate, and the end-to-end delay of the WBAN [7], [8]. Thus, the energy efficiency of WBAN is a critical issue, and it must be addressed in any WBAN system [5].

The most suitable layers to deal with energy efficiency are the network layer (such as the routing technique) and the data link layer (such as a medium access control protocol). Medium access control (MAC) protocol controls and organizes nodes access to the shared wireless medium. MAC is an essential of any communication protocol stack used in any wireless network, which provides the basis for setting Quality of Service (QoS), a high data rate, end-to-end delay, reliability, and decreased energy. The essential task of the MAC protocol is to avoid both collisions. Therefore, all the above issues must be considered when designing MAC protocols.

The problem of saving energy in WBAN has been studied extensively [7]–[11]. Since the sensors usually are battery-powered, reducing the power consumption of the node to prolong the lifetime of the network is essential because the nodes are provided with a limited source of power. Retransmission data due to fading and collision is the primary source of wasted energy, so avoiding collisions is a technique that it is used to achieve better power efficiency [12]–[15].
Also, additional power can be saved by controlling the nodes’ access to the shared wireless medium in the active mode of the superframe. The advantage of this approach is that it provides additional opportunities to save more power in the WBAN without having a negative impact on other important performance metrics [16], [17].

The diversity method is a technique used to combat the effect of fading of the wireless channel. Diversity can be done through the embedded sensors with multiple antennas or utilizing a cooperative communication [18], [19]. Nevertheless, such cooperative communication utilizes extra sub-channels/time slots to transmit a single data symbol from the source to the receiver that reduces the bandwidth efficiency of wireless channels [20], [21].

Different cooperative communications were considered for WBAN to improve their energy efficiency, reliability, and end-to-end delay. In [22], Deepak and Babu investigated the energy efficiency of an incremental relay-based cooperative communication in WBAN, they considered two communication model, the in-body communication between implant sensors and the gateway, and on-body communication between a body surface node and the gateway with line-of-sight (LOS) and non-LOS channels. In [23], Manirabona et al. proposed a Decode and Merge method which maintains the relaying mode by merging frames from relayed and relaying nodes. The throughput has been studied with keeping the energy consumption unchanged. In [24], Esteves et al. introduced a cooperative MAC protocol, named cooperative energy harvesting (CEH)-MAC, that adapts its operation to the energy harvesting (EH) conditions in WBAN. In [25], Link-Aware and Energy Efficient protocol for WBAN (LAEEBA) and Cooperative Link-Aware and Energy Efficient protocol for WBAN (CoLAEEBA) routing protocols are presented, they have investigated the throughput and the network lifetime. In [26], Ahmed et al. introduced a cooperative compressed sensing (CCS) approach, which takes into account the energy efficiency of WBAN by exploiting the benefits of random linear network coding (RLNC). Hiep et al. [27] analyzed and investigated the performance of multiple-hops in WBAN that was based on the IEEE 802.15.6 standard. The authors analyzed the performance of multiple-hops in WBAN, which include multiple node sensors and have many hops according to the power transmitted, the distance between the sensors, and the distance between the sensors and the coordinator. The proposed technique considered the power consumption and compared their protocol with the star-topology scenario. Rout and Das [28] developed a multi-relay, Ultra-Wideband (UWB)-based BAN system. Theoretical and simulation results based on IEEE 802.15.6 with a CM3 channel model were analyzed and discussed. The work generally focused on the study of Amplify-and-Forward (AF) and Decode-and-Forward (DF) relaying and direct transmission for WBAN in the 3.1 - 10.6 GHz UWB band. In [29], Yousaf et al. proposed proactive relays selection for both on-body and in-body WBAN. The results showed that a three-relay, incremental cooperative communication performed better in terms of the probability error rate (PER). In [30], Cui et al. proposed a joint relay selection and power control scheme (JRP) that taking into account transmission reliability. The proposed protocol achieved a good trade-off between reliability and energy consumption. However, the disadvantage of the multi-hop and cooperative communication, as presented in [22]–[30] is that the on-body sensor nodes must retransmit the other sensors’ data in the case of data packet losses, where these nodes may need to transmit twice, i.e., it must transmit its own data and the data of other sensors. This retransmission mechanism results in a reduction of the energy efficiency of the on-body sensors since more energy is consumed in retransmitting the data of other sensors to the destination (gateway). A comparison of the state-of-the-art work is also shown in Table 1.

The limitations of the proposed protocols in [22]–[30] can be elaborated as follows: 1) The relay nodes in the cooperative communication are sensors and they are involved in the retransmitting of the data of other sensors, which reduces the overall energy of WBAN. 2) When the sensors are involved in cooperation, they may have to transmit twice, once for their own data and once for the other sensors’ data. In doing so, the probability of collisions increases, and retransmissions occur, which increases the duty cycles and reduces the energy efficiency of the other sensors. 3) In the WBAN, it is possible that not all sensors have data to transmit in the wakeup period, so involving these sensors in relaying may increase competition, thereby increasing the duty cycles and reducing the energy efficiency.

However, to the best of our knowledge, none of the previous work utilized two master nodes architecture. In this paper, we present Two Master Nodes Cooperative Protocol (TMNCP) based on IEEE 802.15.6 CSMA policy. The contributions of this paper are summarized as follows:

1) We propose incremental cooperative communication that involves master nodes in relaying the data of the sensors instead of other on-body sensors.
2) The belt master node performs all retransmission and cooperation issues, which reduces competition between sensors and lessens the probability of collisions, consequently improving energy efficiency.
3) The master nodes are embedded with double transceivers, one of them is used for communication with the sensors and the other transceiver is used for communication between master nodes. Thus, it is unnecessary to leave time for the master nodes in the time frame, and this reduces the active time of the sensor significantly, also reduces competition between sensors. In addition, the TMNCP does not require a significant change in WBAN 802.15.6 standard and it can be considered as plug and play protocol.
4) We derived the BER of the proposed protocol by taking into account two types of channels, i.e., small-scale and shadowing models. We demonstrated that the proposed
TABLE 1. Comparison of state-of-art work.

<table>
<thead>
<tr>
<th>Ref.</th>
<th>Proposed Protocol</th>
<th>Enhancement</th>
<th>Limitations</th>
</tr>
</thead>
</table>
| [22] | Incremental Relay based Cooperative Communications | • Improves the energy efficiency significantly  
• Optimal packet size | • It burdens sensors nodes in the retransmission process and increases their transmission power  
• Reliability is not considered |
| [23] | Decode and Merge technique (DMT) | • Interference mitigation  
• Throughput  
• Residual energy | • Number of the nodes is not considered |
| [24] | Cooperative Energy Harvesting (CEH)-MAC | • Network throughput  
• Average end-to-end delay  
• Energy efficiency | • It burdens sensors nodes in the retransmission process and increases their transmission power  
• Delay and reliability are not considered |
| [25] | Cooperative Link aware and Energy Efficient (Co-LAEEB) Protocol | • Residual energy increases  
• Throughput  
• Prolong network lifetime | • Does not consider MAC protocol in their analysis  
• Delay is not considered |
| [26] | Cooperative Compressed Sensing (CCS) | • The energy efficiency of the body sensor nodes  
• Low complexity reconstruction algorithm, namely De-correlated Iterative Reweighted Group LASSO (DIG LASSO) | • It burdens sensors nodes in the retransmission process and increases their transmission power  
• Delay is not analyzed  
• MAC protocol is not considered (IEEE 802.15.6) |
| [27] | Multi-hop relaying technique | • Improves network throughput by exploiting multi-hops communications,  
• Achieves high-energy efficiency by reducing the transmission power | • Not suitable for large-scale networks |
| [28] | Multi-relaying for UWB | • Bit error rate  
• Power efficiency | • MAC protocol is not considered (IEEE 802.15.6)  
• It burdens sensors nodes in the retransmission process |
| [29] | Incremental Cooperative Critical Data Transmission in Emergences For Static WBAN (InCo-CESat) | • Improve the reliability  
• Residual energy increases  
• Improve throughput | • MAC protocol is not considered (IEEE 802.15.6)  
• It burdens sensors nodes in the retransmission process and increases their transmission power |
| [30] | A joint relay selection and power control scheme (JRP) | • Improve transmission reliability  
• Average throughput improved | • It burdens sensors nodes in the retransmission process and increases their transmission power  
• MAC is not considered |
| Propos ed work 2018 | Two Master node Cooperative Protocol (TMNCP) | • Duty cycle  
• Bit error rate  
• Power efficiency  
• Energy efficiency | • It does not burden sensors nodes in retransmission process  
• It considers delay, reliability and IEEE 802.15.6 standard |

protocol has reduced duty cycle, average transmission power and achieve better energy efficiency.

The rest of the paper is organized as follows. The system model and the architecture of the proposed protocol are presented in Section 2. In Section 3, the proposed TMNCP is described in detail, including the investigation of Carrier Sense Multiple Access Collision Avoidance (CSMA/CA) based on IEEE 802.15.6 and Duty Cycle and Power Analysis for CSMA/CA based on IEEE 802.15.6 and IEEE 802.15.6 TMNCP. The required parameters, a numerical example, and the analysis of the numerical are provided in Section 4. Section 5 presents our conclusions and the future work we have planned.

II. SYSTEM MODEL AND ARCHITECTURE
A. NETWORK ARCHITECTURE
The IoT (Internet of Things) health network topology states the arrangement of various components of an IoT healthcare network that shows representative scenarios of seamless healthcare environments. Figure 1 refers
to how a heterogeneous computing grid gathers massive amounts of vital signals and sensor data, for example, blood pressure (BP), body temperature, electrocardiograms (ECG), and oxygen saturation and forms a typical IoT Net topology. Vitals are taken using portable medical devices and sensors attached to his or her body. Taken data are then examined and stored, and stored data from different sensors and machines become useful for aggregation. Based on analyses, caregivers can see patients from any place and react accordingly [31].

An example of WBAN architecture is shown in Figure 2 and 3. Sensors are distributed over the surface of the body to gather health data, and sensors transmit the data to the coordinator for analysis. In a WBAN system based on the one-hop star topology, all sensors send their data to the coordinator. In such a scenario, the major causes of power losses in WBAN are, retransmission process due to fading and collisions, idle listening, overhearing, traffic fluctuations, and protocol overhead, the first two of which can be avoided partially or fully by utilizing two masters–slave topology.

In this paper, two masters–slave architecture is proposed. One of the master nodes is fixed on the body, such as a node carried around the belt, which is called the on-body master node (OBN). The other master node functions as a monitor and can receive data from the sensor nodes (slaves) as the carried node can, and it is referred to as the outer master node (OMN). Because of the movement of the body, the distances between the sensor nodes and two master nodes vary.
The proposed protocol can significantly shift the retransmission process from the sensors to the master nodes. Hence, the energy efficiency of the sensors is increased.

**B. COMMUNICATION MODEL OF TMNCP**

The proposed protocol takes into consideration the principle of ARQ, and it works in a cooperative fashion, as follows: in the first phase, the sensor node broadcasts the data to the master nodes (on-body nodes and outer nodes). In the second phase, the OMN checks the received data to determine whether it has been received accurately; then the OMN sends back a positive ACK, and OBN drops the data that have been received from the sensor, as shown in Figure 3. Otherwise, the OMN sends NACK to the OBN, which re-sends the data received from the sensor to the OMN and then combines the signal data of the first and second phases via Maximal Ratio Combining (MRC).

The aims of this work are summarized as follows:
1) Reliability: The proposed protocol is a cooperative protocol, which lowers the probability of losing data by sending data over two independent paths.
2) Reduce the retransmission process due to fading and collision: retransmission process is one of the main factors that is draining the batteries in WBAN. This protocol overcomes this issue by using two-master nodes.
3) Energy efficiency: Since the OBN does retransmission on behalf of the sensors, the number of retransmissions can be reduced, and hence enhance the energy efficiency.

**C. ANALYSIS OF THE DUTY CYCLE AND POWER FOR CSMA/CA BASED ON IEEE 802.15.6**

In this work, CSMA/CA is incorporated in the proposed TMNCP, and the basic procedures of IEEE 802.15.6 are described in detail in [33]. In CSMA/CA, a back-off counter (BO) has a random value between 1 and CW, and CW ∈ (CWmin, CWmax). The values of CWmin and CWmax vary depending on the user’s priorities [33]. The sensor decreases their BO by one for each idle CSMA slot that has a duration equal to pCSMASlotLength and latterly denoted as Ts. If the BO is equal to zero, the sensor sends the frame. If the channel is not free due to the frame is being sent from another node, the node locks its BO until the channel is idle. The CW is doubled for an even number of failures or number of retransmission retrying, and it is maximum value 7 [33].

**III. PROPOSED COOPERATIVE MAC PROTOCOL FOR WBAN**

CSMA/CA and time-division multiple access (TDMA) are suitable MAC protocols for WSN. The performance of CSMA/CA and TDMA in terms of delay and power consumption is reported in [27]. Because multiple WBAN, and WBAN sensors, which frequently access, then leave the medium, may be placed in the same area and share the same transmission range, thus CSMA/CA is preferable to TDMA [32].

**A. COOPERATIVE MAC PROTOCOL FOR WBAN**

A cooperative MAC protocol is proposed in this subsection. Sensors in WBAN are distributed over a limited area, and they usually are equipped with limited source power. Due to the above limitation, it is necessary to have a coordinator node in WBAN, which usually is carried around the belt. A coordinator node usually is embedded with a larger source of power than the sensors are. This network topology can enhance the transmission power and reduce the transmission range for the sensors and for operative CSMA/CA control. In this work, we attempted to design the MAC protocol in order to take care of some important issues:

1) Reliability: The proposed protocol is a cooperative protocol, which lowers the probability of losing data by sending data over two independent paths.
2) Reduce the retransmission process due to fading and collision: retransmission process is one of the main factors that is draining the batteries in WBAN. This protocol overcomes this issue by using two-master nodes.
3) Energy efficiency: Since the OBN does retransmission on behalf of the sensors, the number of retransmissions can be reduced, and hence enhance the energy efficiency.

**B. INVESTIGATION OF CSMA/CA BASED ON IEEE 802.15.6**

In this work, CSMA/CA is incorporated in the proposed TMNCP, and the basic procedures of IEEE 802.15.6 are described in detail in [33]. In CSMA/CA, a back-off counter (BO) has a random value between 1 and CW, and CW ∈ (CWmin, CWmax). The values of CWmin and CWmax vary depending on the user’s priorities [33]. The sensor decreases their BO by one for each idle CSMA slot that has a duration equal to pCSMASlotLength and latterly denoted as Ts. If the BO is equal to zero, the sensor sends the frame. If the channel is not free due to the frame is being sent from another node, the node locks its BO until the channel is idle. The CW is doubled for an even number of failures or number of retransmission retrying, and it is maximum value 7 [33].

**C. ANALYSIS OF THE DUTY CYCLE AND POWER FOR CSMA/CA BASED ON IEEE 802.15.6**

In this subsection, we address the duty cycle (DC) and power for the traditional slave-master topology of CSMA/CA based
on IEEE 802.15.6. The average transmission power is related directly to the duty cycle. DC is defined as the ratio of the RF active time to the sleeping time multiplied by the factor (1+PER). DC is expressed as [9]:

\[ DC = \frac{T_{\text{active}}}{T_{\text{Sleep}}} \times (1 + \text{PER}) \]  

(1)

where \( T_{\text{active}} \) is the RF activity time, which is given as [34]:

\[ T_{\text{active}} = T_\text{on} + T_{\text{CW}} + T_{\text{data}} + T_{\text{ACK}} + 2T_{\text{pSIFS}} + 2\alpha \]  

(2)

\( T_{\text{CW}} \) is average contention time and it is given as:

\[ T_{\text{CW}} = 0.5 \text{ CW.T}_{\text{s}} \]  

(3)

The required time to send a data is given as [34]:

\[ T_{\text{DATA}} = T_{\text{P}} + T_{\text{PHY}} + T_{\text{MAC}} + T_{\text{BODY}} + T_{\text{FCS}} \]  

(4)

The acknowledgment sending time is given by:

\[ T_{\text{ACK}} = T_{\text{P}} + T_{\text{PHY}} + T_{\text{MAC}} + T_{\text{FCS}} \]  

(5)

The average probability of error at the packet level at each hop is given as [35], [36]:

\[ \text{PER} = 1 - (1 - \text{BER})^{P_{\text{avg}}} \]  

(6)

The DC is given as:

\[ DC = \frac{T_{\text{on}} + T_{\text{CW}} + T_{\text{data}} + T_{\text{ACK}} + 2T_{\text{pSIFS}} + 2\alpha}{T_{\text{Sleep}}} \times \left( 2 - (1 - \text{BER})^{P_{\text{avg}}} \right) \]  

(7)

The factor, \( 2 - (1 - \text{BER})^{P_{\text{avg}}} \), is taken into account, which shows how the BER influences DC. DC and the average transmission power are affected directly by the factor \( 2 - (1 - \text{BER})^{P_{\text{avg}}} \).

The average transmission power, \( P_{\text{avg}} \), is obtained via multiplying DC, \( V_{dd} \), and \( I_{\text{act}} \), where \( V_{dd} \) is the radiofrequency (RF) of the module supply voltage, and \( I_{\text{act}} \) is RF average active current [9].

\[ P_{\text{avg}} = DC \times V_{dd} \times I_{\text{act}} \]  

(8)

\( T_{\text{Sleep}} \) : Sleep time

\( T_{\text{c}} \) : Total time to transmit packet

\( T_{\text{e}} \) : CSMA slot length or pCSMASlotLength

\( T_{\text{c}} \) : Collision time, \( T_{\text{c}} = T_{\text{active}} \)

\( T_{\text{on}} \) : RF transceiver power-on start time

\( T_{\text{CW}} \) : Average back-off time

\( T_{\text{data}} \) : Time to transmit a data packet

\( T_{\text{ACK}} \) : Time to receive an ACK

\( \text{PER} \) : Packet Error Rate

\( \text{BER} \) : Bit Error Rate

\( \alpha \) : Delay time

\( T_{\text{P}} \) : preamble time

\( T_{\text{PHY}} \) : physical header time

\( T_{\text{MAC}} \) : MAC header

\( T_{\text{BODY}} \) : MAC frame body time

\( T_{\text{FCS}} \) : frame check sequence time

\( \tau \) : Transmission probability

\( P_{\text{length}} \) : Packet length

**D. PROPOSED COOPERATIVE PROTOCOL FOR WBAN**

The main goal of this paper is to evaluate the duty cycle and average transmission power utilizing the IEEE 802.15.6 standard with the proposed cooperative communication. CSMA/CA based on our proposed protocol, TMNCP, is explained as follows. The sensor nodes in the proposed protocol will not change their access algorithm to channel, but instead of the sensor transmitting directly to OBN, the sensor will broadcast the data to OBN and OMN, and this communication occurs in the first phase. Therefore, the sensor will obey the CSMA/CA algorithm provided in Table 2. After OBN and OMN received the data sent by the sensor, the OMN decodes the data. At second phase, if the data have been received correctly, the OMN transmits immediate Acknowledgment (ACK) to the sensors and OBN. Thus, the sensor and OBN know that the packet was delivered correctly, and OBN drops the data received from the sensor. However, if the sensor and OBN do not receive ACK or if the OMN does not decode the data sent by the sensor, the OMN sends a Negative Acknowledgment (N-ACK). The OBN retransmits the data that were received from the sensor in the first phase, and OMN sums the received data via MCR.

The question that must be answered concerns how the master nodes communicate with each other. In fact, there are different options for the communication between OBN and OMN. In this work, it is assumed the master nodes are embedded with double transceivers, one of them is used for communication with the sensors and the other transceiver is used for the communication between master nodes. Thus, it is unnecessary to leave time for OBN in the time frame, and this reduces the active time of the sensor significantly, also reduce competition between sensors. According to proposed protocol TMNCP, if the OMN does not receive the data from

**TABLE 2. CSMA/CA procedure as defined in the IEEE 802.15.6 standard.**

<table>
<thead>
<tr>
<th>Procedure</th>
<th>Sensor Channel Access in WBAN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Require</td>
<td>CWmin, CWmax, BC, and R</td>
</tr>
<tr>
<td>1.</td>
<td>begin</td>
</tr>
<tr>
<td>2.</td>
<td>CWmin is minimum contention window</td>
</tr>
<tr>
<td>3.</td>
<td>CWmax is the maximum contention window</td>
</tr>
<tr>
<td>4.</td>
<td>BC is a backoff time varies from 1 to CWmin</td>
</tr>
<tr>
<td>5.</td>
<td>R is the Maximum number of retransmission retrying</td>
</tr>
<tr>
<td>6.</td>
<td>SENSOR has data to be sent over medium</td>
</tr>
<tr>
<td>7.</td>
<td>SET CW</td>
</tr>
<tr>
<td>8.</td>
<td>SET-BC random value between 1 and CW</td>
</tr>
<tr>
<td>9.</td>
<td>SET R</td>
</tr>
<tr>
<td>10.</td>
<td>For i = R</td>
</tr>
<tr>
<td>11.</td>
<td>BC start decrement by one</td>
</tr>
<tr>
<td>12.</td>
<td>BC reach to Zero &amp; Unlocked</td>
</tr>
<tr>
<td>13.</td>
<td>If the channel free</td>
</tr>
<tr>
<td>14.</td>
<td>Access Success, breaks for</td>
</tr>
<tr>
<td>15.</td>
<td>Endif</td>
</tr>
<tr>
<td>16.</td>
<td>If i = even</td>
</tr>
<tr>
<td>17.</td>
<td>CW = 2 × CW</td>
</tr>
<tr>
<td>18.</td>
<td>Endif</td>
</tr>
<tr>
<td>19.</td>
<td>If CW=CWmax</td>
</tr>
<tr>
<td>20.</td>
<td>breaks for</td>
</tr>
<tr>
<td>21.</td>
<td>Endif</td>
</tr>
<tr>
<td>22.</td>
<td>Endfor</td>
</tr>
</tbody>
</table>
the sensor correctly, the OBN use the second transceiver to retransmit the data to OMN. Table 3 describes the TMNCP.

It is expected that DC of OBN is increased, but the DC of the sensor is reduced or remains unchanged. The proposed protocol decreases the number of retransmissions by the sensor.

### E. BER of TMNCP

The main aim of TMNCP is to minimize the number of retransmissions by the sensor nodes by reducing BER, which has a direct effect on the duty cycle and the average transmission power of each node. The BER of the proposed protocol has two parts, i.e., 1) direct transmission between the sensor nodes and the master nodes, and 2) cooperative transmission, which occurs between the master nodes. The BER of the proposed protocol is given as:

$$BER_{DPSK}^{TMNCP} = \frac{1}{4} \left[ \left( e^{-\gamma_{S,OBM} Z_{S,OBM}} + e^{-\gamma_{S,OMN} Z_{S,OMN}} \right) \left( 1 + e^{-\gamma_{OBN,OMN} Z_{OBN,OMN}} \right) \right]$$

(12)

where $\gamma_{S,OBM}$, $\gamma_{S,OMN}$, and $\gamma_{OBN,OMN}$ are the signal-to-noise ratios between the sensors and OBN, the sensors and OMN, and OBN and OMN, respectively. $Z_{S,OBM}$ is the channel gain between the sensors and OBN, which is represented by the shadowing model. The terms $Z_{S,OMN}^2$ and $Z_{OBN,OMN}^2$ are the channel gain from the sensors to OMN and from OBN to OMN, respectively, which are represented by the Quasi-static model, and it is an exponential random variable with a mean, $|a|^2 = d^{-\nu}$, and a variance of unity. By inserting the (12) in (7), then inserting the new DC in (8), we can obtain the average transmission power of the proposed protocol.

### F. Energy Efficiency of TMNCP

The energy efficiency ($\Gamma$) is defined as the energy required to successfully transmit and receive bits without errors divided by the total energy required to transmit and receive bits successfully, and it is expressed as:

$$\Gamma = \frac{P_{in} (1 - BER_{DPSK}^{TMNCP}) E_{tr}}{E_{tr.data} + E_{tr.ACK}/NACK}$$

(13)

where $E_{tr}$ is energy is $E_{tx} + P_i/R_i$; $E_{tx}$ and $E_{tx}$ are the energies required for the transmitter and receiver to transmit and receive one bit; $P_i$ is the transmission power; and
TABLE 4. Comparison of the energy efficiency of TMNCP and the protocol proposed in [29].

<table>
<thead>
<tr>
<th>Distance (m)</th>
<th>TMNCP</th>
<th>Protocol proposed in [29]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2</td>
<td>69%</td>
<td>22%</td>
</tr>
<tr>
<td>0.5</td>
<td>59%</td>
<td>11%</td>
</tr>
<tr>
<td>0.9</td>
<td>55%</td>
<td>0%</td>
</tr>
</tbody>
</table>

$E_{TMNCP}^{tr.data}$ is the total energy consumed in the transmission of a data packet with TMNCP. The term $E_{TMNCP}^{tr.data}$ is expressed as:

$$
E_{TMNCP}^{tr.data} = P_{\text{Ingh}}(E_{tx} + P_t/R)(BER_{S, OBN}^d \cdot BER_{S, OMN}^d) \quad \text{First Phase}
$$

$$
+ P_{\text{Ingh}}E_{rx}(1 - BER_{S, OMN}^d) \cdot BER_{S, OBN}^d \cdot BER\text{coop}_{S, OBN, OMN} \quad \text{Second Phase}
$$

In Eq. (14), $E_{tx}$ and $E_{rx}$ are the energies required for the transmitter and receiver to transmit and receive one bit, respectively. The first phase represents energy consumption by the sensor to broadcast the packet from the sensor to OBN and OMN, and the second phase represents energy consumption by the sensor to transmit the packet from OBN to OMN, and the sensor will only overhear the packet from OBN.

$E_{TMNCP}^{tr.ACK/NACK}$ is the total energy consumed in the transmission of ACK and NACK with TMNCP:

$$
E_{TMNCP}^{tr.ACK/NACK} = A_{ACK/NACK} \left( (E_{tx}) (BER_{S, OBN}^d \cdot BER_{S, OMN}^d) \right) \quad \text{First Phase}
$$

$$
+ (E_{rx})((1 - BER_{S, OMN}^d) \cdot BER_{S, OBN}^d \cdot BER\text{coop}_{S, OBN, OMN}) \quad \text{Second Phase}
$$

where $A_{ACK/NACK}$ is the size of ACK/NACK in bits. The first phase and second phase represent energy consumption due to the overhearing of ACK/NACK by the source sensor.

Inserting Eq. (14) and Eq. (15) into Eq. (13), we can obtain the energy efficiency of TMNCP. Table 4 shows that the TMNCP outperformed the incremental relay that was proposed in [29] in terms of the energy efficiency. The evaluation parameters used in the Table 4 are as follows: both $E_{tx}$ and $E_{rx}$ are 50 nJ/bit, $P_{\text{Ingh}} = 500$ bits, $A_{ACK/NACK} = 64$ bits, $n = 4$, transmission rate $k_{act} = 2$ Mbps, the shadowing variance $\sigma_{S, OBM}^2 = 5$ dB, and $P_t = 1000$ mW.

The results show that TMNCP outperformed the protocol proposed in [29] in terms of energy efficiency, where, even for greater distance between the sensors, the TMNCP had better performance than was achieved in [29].

IV. NUMERICAL ANALYSIS FOR TMNCP IN WBAN

A. REQUIRED PARAMETERS AND NUMERICAL EXAMPLE

In this section, the numerical parameters and an example are described. The $R_{\text{act}}$ is 75.9 Kbps. RF transceiver power-on start time (in seconds) for AD7020: $T_{on} = 2$ ms. The minimum of $CW_{\text{min}}$ is 16 slots, and the maximum of $CW_{\text{max}}$ is 64 slots. Hence, the average back-off time is given as $(CW_{\text{min}}T_s)/2$, where each CSMA slot length, $T_s = 125$ $\mu$s. The short interframe spacing time for CSMA/CA of $802.15.6$: $T_{PSIFS} = 50$ $\mu$s. The payload of MAC frame (frame body) is 250 Kbit, and the time required to transmit 250 Kbit: $T_{body} = (250 \times 8)/((75.9 \times 1024)) = 25.7$ ms. The frame header and frame check sequences were 56 and 16 bits, respectively.

Then the $T_{MAC} = 56/(75.9 \times 1024) = 0.72$ ms and $T_{FCS} = 16/(75.9 \times 1024) = 0.205$ ms. The time required to the physical header is 40 $\mu$s. The preamble bits are 88 bits, hence the time required to transmit 88 bits is $88/(75.9 \times 1024) = 1.13$ ms. The delay time $\alpha = 1$ $\mu$s.

The BER parameters are explained here, and they depend on the signal-to-noise ratios, the distance, the shadowing model, and the quasi-fading components. The maximum distance between sensors and OBN was $1m$, then the path loss exponential, $\nu$, varied between 2 and 6, depending on the obstacles. In this work, we assumed that $\nu = 2$. The shadowing variance was varied between 0 and 12. Fading is an exponentially distributed random variable with the mean value $1/\delta$, and the average channel power was defined as $1/\delta = E[|X[i]|^2] = d^{-\nu}$. For simplicity, the packet length was assumed to be 1. The duty cycle of the $802.15.6$ standard using DPSK modulation is:

$$
DC = \frac{T_{\text{act}}}{T_{\text{sleep}}} \left( 2 - \left( 1 - \frac{1}{2}e^{-\gamma_{i,j}|a_{ij}|^2} \right) P_{\text{Ingh}} \right)
$$

The $T_{act} = 2$ ms + $1$ ms + 27.795 ms + 2.095 ms + 0.1 ms + 0.002 ms = 32.992 ms, the $T_{sleep} = 1$ s. The BER is 0.3645 of the DPSK for $\gamma_{i,j} = -5$ dB = 0.316, and $1/\delta = d^{-\nu} = 1$. Hence, the duty cycle is:

$$
DC = \frac{32.992 \times 10^{-3}}{1} = 45.02 \times 10^{-3}
$$

The average transmission power of the RF module supply voltage: $V_{dd} = 3$ V and the RF average active current: $I_{\text{act}} = 15.05$ mA.

$$
P_{\text{avg}} = DC \times V_{dd} \times I_{\text{act}} = 45.02 \times 10^{-3} \times 3 \times 15.05 \times 10^{-3} = 2.03$ mW
$$

Now, let’s examine the average transmission power of the proposed protocol. The active time and sleep time do not change, hence, $T_{\text{act}} = 32.992$ ms, and the sleep time is 1 s. The $d_{S, OBM}^v = 1$ for $n = 2$, $d_{S, OMN}^v = 4$ for $n = 2$, and $d_{S, OBM, OMN}^v = 1$ for $v = 2$. The shadowing variance $\sigma_{S, OBM}^2 = 5$ dB = 3.16. The signal-to-noise ratios are assumed
to be equal between links sensor-OBN, sensor-OMN, and OBN-OMN, which is $-5 \text{ dB} = 0.316$. The $BER_{DPSK}^{TMNCP}$ is:

$$BER_{DPSK}^{TMNCP} = \frac{1}{4} \left[ e^{-\frac{0.316}{10^5} \cdot 0.3162} \right] + \left[ \left( 1 - \frac{1}{2} e^{-0.3162} \right) \cdot e^{-\frac{0.316}{10^5} \cdot 0.31613} \right]$$

$$= 0.25 (0.34 + 0.0759 \times 0.368 \times 0.268) = 0.08$$

due to the distance between nodes.

therefore, the duty cycle is:

$$DC_{TMNCP} = \frac{32.992 \times 10^{-3}}{1s} \cdot (2 - (1 - 0.08))^1$$

$$= 35.63 \times 10^{-3}$$

Then, the average transmission power is:

$$P_{avg}^{TMNCP} = DC_{TMNCP} \times V_{dd} \times I_{act}$$

$$= 35.63 \times 10^{-3} \times 3\times 15.05 \times 10^{-3} = 1.6 \text{ mW}$$

It is observed an increase by a factor of 0.21 was achieved by our proposed protocol.

B. NUMERICAL RESULTS AND DISCUSSION

In this subsection, the performance of the TMNCP protocol is evaluated in terms of BER, duty cycle, and average transmission power. In the evaluation, we assumed the same SNR from the sensors to OBN, OBN to OMN, and sensors to OMN, while the distances between nodes were assumed to be different.

Figure 4 shows a comparison of BER of the direct transmission 802.15.6 standard and TMNCP for difference-normalized distances of $d_{SOBN} = \{0.5, 0.75, 1\}$ and $d_{SOMN} = \{0.5, 0.75, 2\}$ over varying SNR, i.e., $\{-5, -4, -3, \ldots, 5\}$. The important results that can be seen in the figure are summarized as follows:

1) The direct transmission had less performance compared to TMNCP, where BERs appeared less for TMNCP.
2) At $\sigma_{SOBN} = 5dB$, the BER is high compared to $\sigma_{SOBN} = 7dB$ and $9dB$ for TMNCP.
3) The BERs of TMNCP decreased as the distances between the nodes decreased.
4) At high SNR and at $\sigma_{SOBN} = 9dB$, the BER of the TMNCP has better performance compared to the direct transmission.
5) At low SNR and at $\sigma_{SOBN} = 5dB$ and $7dB$, the BER of the direct transmission approach the BER of TMNCP. However, At low SNR and at $\sigma_{SOBN} = 9dB$, the BER of TMNCP show better performance compared to the direct transmission.

Figure 5 shows the comparison of the DCs of direct transmission and TMNCP for difference-normalized distances of $d_{SOBN} = \{0.5, 0.75, 1\}$ and $d_{SOMN} = \{0.5, 0.75, 2\}$ over SNRs of $\{-5, -4, -3, \ldots, 5\}$. The important results that can be seen in the figure are summarized as follows:

1) The DCs of direct transmission were greater than the DCs of TMNCP because the proposed protocol had better performance in the term of BER than the direct transmissions that directly affect and reduce the DC.
2) When the sensors and the master nodes were close to each other, the duty cycles were reduced due to the distance between the nodes being less, which reduced the BER, that lead to a direct reduction in the duty cycle.
3) Larger shadowing parameters reduces the DCs because the shadowing variance improved the quality of the...
of TMNCP with respect to the proposed protocol of [29] is improved by factor of 0.69. Furthermore, the BER of the TMNCP is reduced by a factor of four compared to the direct transmission.

In future work, we will analyze the proposed protocol using a cognitive network that allows two different sensor nodes to use dynamic spectrum allocation that reduces competition on the single spectrum.

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FIGURE 6. Average transmission power comparison against SNR for ν = 2.

V. CONCLUSION

In this paper, we have presented a TMNCP that improved reliability, average transmission power, and energy efficiency of WBAN. TMNCP was transmitting the data over two independent paths with the help two master nodes. It is worked within two phases: a broadcast phase by which the on-body sensor transmitted the data to the master nodes, and the second phase where the master nodes cooperatively exchange data received from the sensor. TMNCP enabled two master nodes in WBAN systems which assisted the sensors to retransmit the corrupted data and hence enhanced their energy efficiency. The results showed that the proposed protocol is better than direct transmission when the distances between nodes are reduced and the shadowing variance is increased. It was also observed that the average transmission power was decreased by a factor of 0.21 when the TMNCP protocol was used. In addition, we have shown that the energy efficiency links and reduced BER, which consequently reduced the DCs.

4) At high SNR, the DCs of direct transmission and TMNCP are approximately the same.

5) At low SNR, the DCs of TMNCP have better performance compared to the DC of the direct transmission.

Figure 6 shows the comparison of average transmission power over SNR. It is clear that the average transmission power is less using the proposed protocol. The average transmission power was reduced more when the distances between the nodes were reduced and the shadowing variance increased. At SNR equal to -4 dB, the improvement achieved by the proposed protocol was 12.7% at the shadowing variance of 9 dB. However, the average transmission power of the proposed protocol and direct transmission are equal for the large SNR.


**DHALAL ABDULMOHISN HAMMOOD** received the B.Sc. degree in computer engineering and data technology from the University of Technology, Baghdad, in 2003, and the M.Sc. degree in computers engineering techniques from the Electrical Engineering Technical College, Middle Technical University, in 2011. She is currently pursuing the Ph.D. degree with the School of Computer and Communication Engineering, Universiti Malaysia Perlis, Perlis, Malaysia. She contributed in organizing several IEEE conferences in Malaysia in 2010 and 2011, in Egypt, Jordan, and Ukraine, in 2010, 2013, and 2016, respectively. Her research interests include computer networks security, cryptography, artificial intelligence—artificial neural networks, genetic algorithms, wireless sensor networks, and wireless body area networks.

**HASILZA A RAHIM** received the bachelor’s degree in electrical engineering from the University of Southern California, Los Angeles, CA, USA, in 2003, the master’s degree in electronics design system from Universiti Sains Malaysia, Pulau Pinang, Malaysia, in 2006, and the Ph.D. degree in communication engineering from Universiti Malaysia Perlis, Perlis, Malaysia, in 2015. In 2018, she joined the School of Computer and Communication Engineering (SCCE), Universiti Malaysia Perlis (UniMAP), as a Lecturer, where she is currently a Senior Lecturer. She is the Programme Chairperson postgraduate studies at the SCCE, UniMAP. She is a Researcher with the Bioelectromagnetics Research Group, SCCE. She was leading Malaysian Communications and Multimedia Commission Research Grant (worth U.S. $150k). She has been mentoring several undergraduate and about 12 graduate students. She has authored and co-authored about 100 leading international technical journal and peer-reviewed conference papers, including three articles in Nature Publishing Group journals (Scientific Reports), three patents, and two book chapters. Her research interests include wearable and conformal antennas, metamaterials, antenna interaction with human body, on-body communications, green microwave absorbers, wireless body area networks, bioelectromagnetics, physical layer protocols for WBAN, and 5G massive multiple input-multiple-output systems. Several research funds were granted nationally and internationally, such as Fundamental Research Grant Scheme, National Science Fund, and Short Term Grant of UOWD (worth U.S. $375k). She has been a member of the technical program committees of several IEEE conferences and technical reviewer for several IEEE and other conferences. She is a Member of the IEEE and IEEE MTT-S, and a Graduate Member of the Board of Engineers Malaysia. As an advisor, her supervised projects have also won prizes, such as the Third Place in IEEE Malaysia Section Final Year Project Competition (Telecommunication Track) in 2017. She was recognized as the Excellence Woman Inventor by UniMAP in 2011 and Silver medal at the International Invention, Innovation & Technology Exhibition (ITEX 2018).

**R. BADLI SHAH AHMAD** received the B.Eng. degree (Hons.) in electrical and electronic engineering from Glasgow University, in 1994, and the M.Sc. degree in optical electronic engineering and Ph.D. degree from the University of Strathclyde, in 1995 and 2000, respectively. His research interests are in computer and telecommunication network modeling using discrete event simulators, optical networking, and embedded system based on GNU/Linux.

**AHMED ALKHAYYAT** received the B.Sc. degree in electrical engineering from AL KUFA University, Najaf, Iraq, in 2007, and the M.Sc. degree from the Dehradun Institute of Technology, Dehradun, India, in 2010. He is currently the Dean of international relationship and the Manager of the word ranking at Islamic university, Najaf. His research interests include network coding, cognitive radio, efficient-energy routing algorithms and efficient-energy MAC protocol in cooperative wireless networks and wireless local area networks, and cross-layer designing for self-organized network. He contributed in organizing several IEEE conferences, workshop, and special sessions. To serve his community, he acted as a reviewer for several journals and conferences.

**MOHAMMAD EZANNI MAT SALLEH** received the B.Eng. degree (Hons.) in electrical engineering from Universiti Teknologi MARA and the M.Sc. and Ph.D. degrees in electrical system engineering from Universiti Malaysia Perlis. He is currently the Director of the State of Johor Department of Environment, Malaysia.
MOHAMEDFAEQ ABDULMALEK has published 12 journals and three conference proceedings, in 2017. The University of Wollongong in Dubai (UOWD) has published a total of 31 journals and 14 conference proceedings, in 2017. Hence, he has contributed 38.7% of the UOWD’s total number of journals, in 2017, and therefore, he is ranked first in UOWD. He is ranked fourth in the UAE for the number of articles published in 2017, after Prof. R. M. Shubair, K. Salah, and G. McCay from Khalifa University. He has published one article in Scientific Reports (Nature publishing Group), in 2017 (Only two other universities in the UAE published in Scientific Reports in 2017: Khalifa University of Science and Technology and United Arab Emirates University). He has also published one article in Scientific Reports (Nature publishing Group), in 2016. He has achieved 1529 citations and H-index of 18 (ranked first in UOWD). Dr. Abdulmalek has achieved 1141 total number of reads in ResearchGate out of 2575 total number of reads for UOWD, in 2017. Therefore, he has contributed 44.3% of the UOWD’s total number of reads, in 2017. He has achieved 811 total number of reads in ResearchGate out of 1499 total number of reads for UOWD in the first week of October 2017. Hence, he has contributed 54.1% of the UOWD’s total number of reads in the first week of October 2017. He has achieved 43 942 total number of reads in ResearchGate (ranked first in UOWD and ranked fourth in the UAE). He has been shortlisted for the final presentation of Expo2020 Innovation Impact Grant, in 2017 (UOWD was the only university in the UAE shortlisted for the final presentation, in 2017). In 2017, he received AED 20,000 from the UOWD Grant. In 2016, he received AED 20,000 from the UOWD Grant. He has published a total of 64 publications in the past two years, from 2015 to 2017 (17 JCR-indexed journals, 32 SCOPUS-indexed journals, and 15 conference proceedings).

MUZAMMIL JUSOH received the bachelor’s degree in electrical, electronic and telecommunications engineering and the M.Sc. degree in electronic telecommunication engineering from Universiti Teknologi Malaysia, in 2006 and 2010, respectively, and the Ph.D. degree in communication engineering from Universiti Malaysia Perlis (UniMAP), in 2013. He was an RF and Microwave Engineer with Telekom Malaysia Berhad (TM) Company, from 2006 to 2009. He was an Engineer (Team Leader) with the Specialized Network Services Department, TM Senai, Johor. He was involved in the preventive and corrective maintenance of ILS, NDB, DVOR, repeater, microwave system, VHF, and UHF based on contract. He was with the Department Civil Aviation, TUDM, PDRM, ATM, Tanjung Pelepas Port, MCMC, and JPS (Hidrologi Department). He is currently an Associate Professor and a Researcher with the School of Computer and Communication Engineering, UniMAP. He is supervising a number of Ph.D. and M.Sc. students and also managing a few grants under the Ministry of Higher Education Malaysia. He has published a number of papers in quality journals, such as the IEEE Antennas and Wireless Propagation Letters, Microwave and Optical Technology Letters, International Journal of Antennas and Propagation, Progress in Electromagnetics Research, and Radio Engineering and over 70 conference papers. His research interests include antenna design reconfigurable antennas, multi-in multi-out, ultra-wideband, and wireless communication systems.

QAMMER H. ABBASI received the B.Sc. and M.Sc. degrees (Hons.) in electronics and telecommunication engineering from the University of Engineering and Technology (UET), Lahore, Pakistan, and the Ph.D. degree in electronic and electrical engineering from the Queen Mary University of London (QMUL), U.K., in 2012. In 2012, he was a Post-Doctoral Research Assistant with the Antenna and Electromagnetics Group, QMUL. From 2012 to 2013, he was an International Young Scientist with the National Science Foundation, China, and an Assistant Professor with UET. From 2013 to 2017, he was with the Center for Remote Healthcare Technology and the Wireless Research Group, Department of Electrical and Computer Engineering, Texas A&M University (TAMUQ), as an Assistant Research Scientist and was then promoted to an Associate Research Scientist and a Visiting Lecturer, where he was leading multiple Qatar National Research Foundation grants (worth U.S. $3 million). He is currently a Lecturer (Assistant Professor) with the School of Engineering, University of Glasgow. He is also a Visiting Research Fellow with QMUL and a Visiting Associate Research Scientist with TAMUQ. He has been mentoring several undergraduate, graduate students, and post-doctoral researchers. He has a research portfolio of around U.S. $3 million and has contributed to a patent, five books, and over 100 leading international technical journal and peer-reviewed conference papers. His research interests include nano-communication, RF design, and radio propagation, biomedical applications of millimeter and terahertz communication, wearable and flexible sensors, compact antenna design, antenna interaction with human body, implants, body-centric wireless communication issues, wireless body sensor networks, non-invasive health care solutions, physical layer security for wearable/implant communication, and multiple-input-multiple-output systems. He is a member of the IET and a Committee Member of the IET Antenna and Propagation and the Healthcare Network. He has been a member of the technical program committees of several IEEE flagship conferences and a technical reviewer for several IEEE and top-notch journals. He has contributed to organizing several IEEE conferences, workshops, and special sessions in addition to the European School of Antenna Course. He received several recognitions for his research. He was the Chair of the IEEE Young Professional Affinity Group. He is currently an Associate Editor of the IEEE Access journal. He acted as a Guest Editor for numerous special issues in top-notch journals.

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