Reliable emergency data transmission using transmission mode selection in wireless body area network

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Abstract: The main differences between wireless body area network (WBAN) and wireless sensor network are the sensors in WBAN distributed on the human body; therefore, body posture, clothing, muscle movement, body temperature, and climatic conditions generally influence the links between sensors and destination. Second, data gathered by the sensors are related to human life; therefore, it is important to make sure that the gathered data should be delivered to destination efficiently. Hence, in some cases, single-hop transmission or direct transmission mode (DTM) is not sufficient to deliver the data to the destination. In this paper, we proposed an emergency-based cooperative communication protocol for WBAN, named as Emergency Data Transmission using Transmission Mode Selection (ED-TMS) protocol based on the IEEE 802.15.6 CSMA. First, a complete study of a system model is inspected in terms of channel path loss, successful transmission probability, and the outage probability. Second, a mathematical model of the proposed protocol, end-to-end delay, and throughput with relay selection (RS) is derived. Third, RS is utilized along with ED-TMS, which makes only the best relay participate in cooperation in a distributed manner. The design objective of the ED-TMS is to reduce end-to-end delay and enhance the throughput of direct transmission and traditional cooperative communication. The simulation and numerical results show that the ED-TMS can enhance network performance under general conditions.

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PUBLIC INTEREST STATEMENT
Wireless body area sensor network has a huge potential to revolutionize the future of healthcare monitoring by diagnosing many life-threatening diseases and providing real-time patient monitoring. Demographers have predicted that the worldwide population aged over 65 will have doubled in 2025 to 761 million from the 1990 population of 357 million. This implies that by 2050, medical aged care will become a major issue. Where sensors in such network attached on/in and off the body, each sensor equipped with a wireless transceiver. The equipped transceiver utilizes radio frequency to transmit the gathered data. The wireless channel is error prone that sometimes makes the direct transmission not possible. In this work, we proposed a method that allows sensors to cooperate with each other to deliver the data efficiently.
compared to DTM IEEE 802.15.6 CSMA and benchmark. The end-to-end delay reductions of ED-TMS with RS with respect to DTM, mutual information incremental cooperative communication, and ED-TMS without RS are 24.5%, 28%, and 30%, respectively.

Subjects: Electrical & Electronic Engineering; Communications & Information Processing; Communication Networks & Systems; Communications System Design; Digital & Wireless Communication

Keywords: wireless body area network; incremental cooperative communication; relay selection technique; outage and successful probability; critical data index; end-to-end delay; throughput

1. Introduction
Wireless body area networks (WBANs) are communication networks of sensor nodes (and/or actuators) placed on, inside, or around the human body that show a new generation of WPAN and introduce several challenges for implementation. Sensor nodes in WBANs are small and embedded with finite source compared to devices in the traditional wireless sensor network. Finite source makes a limitation on the energy spent by sensor nodes in sensing, processing, storing, and delivering the data (Arain & Ghani, 2016; Cavallari, Martelli, Rosini, Buratti, & Verdone, 2014; Hayajneh, Almashaqbeh, Ullah, & Vasilakos, 2014; Khan & Pathan, 2018; Liu, Yuen, Cao, Hassan, & Chen, 2014; Mahapatra, Nisar, Kaddoum, Hassan, & Yuen, 2016).

The end-to-end delay and throughput are the key factors to determine the overall performance of a WBAN. The most suitable layers to address the aforementioned factors are data link layer, such as medium access control (MAC) protocol and physical layer (such as virtual diversity technique) (Abbasi, Rehman, Qaraqe, & Alomainy, 2016; Alomainy, Bari, Abbasi, & Chen, 2014; Rasheed et al., 2017). MAC protocol is controlling and organizing sensor node access to the wireless shared medium. MAC protocol is an essential protocol which considers the basis for setting Quality of Service, high data rate, and higher energy saving in any wireless networks. In addition, the MAC protocol is preventing collisions and concurrent sending while conserving data rate, reducing end-to-end delay, enhancing the reliability, and saving the energy (Chavez-Santiago et al., 2013; Khan, Ullah, Alam, & Kwak, 2015; Tachtatzis, Di Franco, Tracey, Timmons, & Morrison, 2010; Ullah, Imran, & Alnuem, 2014).

Diversity technique is the method to combat the effect of the fading of the wireless channel; diversity can be achieved through either embedded sensor node with multiple antennas or using cooperative communication (CC) (Elfittiti, Hamouda, & Ghrayeb, 2009; Ibrahim, Sadek, Weifeng, & Liu, 2008). Various types of CCs are considered in WBANs to improve their performance in terms of power saving, reliability, and end-to-end delay. Whereas in the conventional CC, a source sends data to a one of the on-body sensor nodes and to the destination, and then the intermediate node(s) (relay(s)) retransmit what was sent by the source node to the destination (Nhu, Bao, & Beongku, 2016). However, such CCs utilized extra sub-channels/time slots to transmit single data from the source to the receiver which increases the delay and reduces the bandwidth efficiency of wireless channels (Alkhayyat & Sadkhan, 2018; Alkhayyat, Gazi, & Sadkhan, 2015). Therefore, it is possible to solve the aforementioned problem of the conventional CC by utilizing an incremental cooperative communication (ICC) in such a way that the relay node does not participate in cooperation until the destination does not receive what was sent by the source correctly (Alkhayyat, 2015). CCs have been widely considered in the literature for WBAN systems (Cui, Sun, Wang, & Yuefeng, 2017; Rout & Das, 2016b, 2017; Rout, Gurala, & Das, 2016; Shimly, Movassaghi, & Smith, 2016; Wei, Sun, & Yuefeng, 2017; Yan, Peng, Shen, Yan, & Deng, 2018; Zhang, Zhang, & Zhang, 2017); however, in this paper, only the ICC is surveyed.
Different CCs were considered for WBAN to improve their throughput and end-to-end delay. Deepak and Babu (2015) investigated the energy efficiency of an incremental relay-based cooperative communication in WBANs, and they considered two communication models: 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. Manirabona, Fourati, and Boudjit (2015) 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. Esteves et al. (2015) introduced a cooperative MAC protocol, named cooperative energy harvesting-MAC, that adapts its operation to the energy harvesting conditions in WBANs. In Lalos et al. (2015), Link-Aware and Energy Efficient protocol for WBANs (LAEEBA) and Cooperative Link-Aware and Energy Efficient protocol for WBANs (CoLAEEBA) routing protocols are presented, and they have investigated the throughput and the network lifetime. Ahmed et al. (2015) introduced a cooperative compressed sensing approach, which takes into account the energy efficiency of WBANs by exploiting the benefits of random linear network coding (RLNC). Hiep, Hoang, and Kohno (2015) analyzed and investigated the performance of multiple hops in WBANs that was based on the IEEE 802.15.6 standard. The authors analyzed the performance of multiple hops in WBANs, 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 (2016a) developed a multi-relay, ultra-wideband (UWB)-based Body area network (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 and Decode-and-Forward relaying and direct transmission for WBANs in the 3.1–10.6 GHz UWB band. Yousaf et al. (2016) proposed proactive relay selection (RS) for both on-body and in-body WBANs. The results showed that a three-relay, incremental cooperative communication performed better in terms of the probability error rate. Cui, Sun, Wang, and Ji (2017) proposed a joint RS and power control scheme (JRPC) that takes into account transmission reliability. The proposed protocol achieved a good trade-off between reliability and energy consumption. In Liao, Leeson, Cai, Ai, and Liu (2018), a mutual information incremental cooperative communication (MI-ICC) protocol is presented, where several on-body relay nodes and one coordinator are attached to the clothes of a patient. MI-ICC achieves better performance in comparison to the two-relay based scheme. Here, the residual energy and network lifetime are taking into account and have improved.

In what follows, the drawbacks and limitations of Ahmed et al. (2015), Cui et al. (2017), Esteves et al. (2015), Hiep et al. (2015), Ibrahim, Han, and Liu (2008), Lalos et al. (2015), Liao et al. (2018), Manirabona et al. (2015), Rout and Das (2016a), and Yousaf et al. (2016) are shown in Table 1. The limitation of Ahmed et al. (2015), Cui et al. (2017), Deepak and Babu (2015), Esteves et al. (2015), Hiep et al. (2015), Lalos et al. (2015), Liao et al. (2018), Manirabona et al. (2015), Rout and Das (2016a), and Yousaf et al. (2016) can be summarized as follows: MAC protocol was not considered (IEEE 802.15.6), end-to-end was not analyzed, best relay node selection is not considered, throughput is not analyzed, and types of gathered data. To address the aforementioned issues and facilitate CC in WBAN, we propose a novel Emergency Data Transmission using Transmission Mode Selection (ED-TMS) protocol based on the IEEE 802.15.6 CSMA. The contributions of this work are summarized as follows:

1. A MAC protocol for the ED-TMS is proposed to coordinate the sensor nodes to act as relay nodes to carry out the retransmission process.
2. Transmission mode selection is considered, where cooperation transmission mode is selected only if the source to destination link is worse than the source to relay and relay to destination links. The best relay is selected to participate in cooperation along with cooperation transmission.
| Ref. | Proposed protocol | Enhancement | Limitations |
|------|------------------|-------------|-------------|
| (Deepak & Babu, 2015) | Incremental relay-based cooperative communications | • Improves the energy efficiency significantly  
• Evaluates the optimal packet size | • MAC protocol is not considered (IEEE 802.15.6).  
• End-to-end Delay is not analyzed.  
• Best relay node selection is not considered.  
• Types of the gathered data are not considered  
• Throughput is not analyzed |
| (Manirabona et al., 2015) | Decode and Merge technique (DMT) | • Interference mitigation  
• Throughput  
• Residual energy. | • MAC protocol is not considered (IEEE 802.15.6).  
• End-to-end delay is not analyzed.  
• Best relay node selection is not considered.  
• Types of the gathered data are not considered  
• Throughput is not analyzed |
| (Esteves et al., 2015) | Cooperative energy harvesting (CEH)-MAC | • Network throughput  
• Average end-to-end delay  
• Energy efficiency | • MAC protocol is not considered (IEEE 802.15.6).  
• Best relay node selection is not considered.  
• Types of the gathered data are not considered |
| (Lalos et al., 2015) | Cooperative link aware and energy efficient (Co-LAEEBA) protocol | • Increases residual energy  
• Throughput  
• Prolongs network lifetime | • MAC protocol is not considered (IEEE 802.15.6).  
• End-to-end delay is not analyzed.  
• Best relay node selection is not considered.  
• Types of the gathered data are not considered |
| (Ahmed et al., 2015) | Cooperative compressed sensing (CCS) | • The energy efficiency of the body sensor nodes  
• Low-complexity reconstruction algorithm, namely de-correlated iterative reweighed group  
• LASSO (DIG LASSO) | • MAC protocol is not considered (IEEE 802.15.6).  
• End-to-end delay is not analyzed.  
• Best relay node selection is not considered.  
• Types of the gathered data are not considered  
• Throughput is not analyzed |

(Continued)
| Ref.                  | Proposed protocol                                             | Enhancement                                                                 | Limitations                                                                 |
|----------------------|----------------------------------------------------------------|------------------------------------------------------------------------------|----------------------------------------------------------------------------|
| (Hiep et al., 2015)  | Multi-hop relaying technique                                 | • Improves network throughput by exploiting multi-hops communications       | • MAC protocol is not considered (IEEE 802.15.6).                           |
|                      |                                                                | • Achieves high-energy efficiency by reducing the transmission power.        | • End-to-end delay is not analyzed.                                         |
|                      |                                                                |                                                                              | • Best relay node selection is not considered.                              |
|                      |                                                                |                                                                              | • Types of the gathered data are not considered.                            |
| (Rout & Das, 2016a)  | Multi-relaying for UWB                                        | • Bit error rate                                                            | • MAC protocol is not considered (IEEE 802.15.6).                           |
|                      |                                                                | • Power efficiency                                                          | • End-to-end delay is not analyzed.                                         |
|                      |                                                                |                                                                              | • Best relay node selection is not considered.                              |
|                      |                                                                |                                                                              | • Types of the gathered data are not considered.                            |
|                      |                                                                |                                                                              | • Throughput is not analyzed.                                               |
| (Yousaf et al., 2016)| Incremental Cooperative Critical Data Transmission in Emergencies For Static WBAN (InCo-CEStat) | • Improves the reliability                                                  | • MAC protocol is not considered (IEEE 802.15.6).                           |
|                      |                                                                | • Increases the residual energy                                              | • End-to-end delay is not analyzed.                                         |
|                      |                                                                | • Improves the throughput                                                   | • Best relay node selection is not considered.                              |
|                      |                                                                |                                                                              | • Types of the gathered data are not considered.                            |
| (Cui et al., 2017)   | A joint relay selection and power control scheme (JRP)       | • Improves transmission reliability                                          | • MAC protocol is not considered (IEEE 802.15.6).                           |
|                      |                                                                | • Improves average throughput                                                | • End-to-end delay is not analyzed.                                         |
|                      |                                                                |                                                                              | • Best relay node selection is not considered.                              |
|                      |                                                                |                                                                              | • Types of the gathered data are not considered.                            |
| (Liao et al., 2018)  | A mutual information (MI)-based ICC                          | • Network lifetime                                                          | • MAC protocol is not considered (IEEE 802.15.6).                           |
|                      |                                                                | • Residual energy                                                           | • End-to-end delay is not analyzed.                                         |
|                      |                                                                | • Number of packets transmitted                                              | • Best relay node selection is not considered.                              |
|                      |                                                                |                                                                              | • Types of the gathered data are not considered.                            |
|                      |                                                                |                                                                              | • Throughput is not analyzed.                                               |
(3) Gathered data nature has been taking into account, where critical data transmitted over ICC and normal data transmitted over direct transmission mode (DTM).

(4) The end-to-end delay and throughput are mathematically modeled and analyzed along with ED-TMS. We show that the proposed protocol can reduce the end-to-end delay and enhance the throughput of the WBAN compared to the existing work and DTM under IEEE 802.15.6 CSMA policy.

The rest of the paper is organized as follows: System model and architecture is presented in Section 2. Section 3 describes and investigates the wireless link and successful transmission probability under the shadowing model. Then, modeling and formulating of ED-TMS in detail have been described in Section 4. In Section 5, end-to-end delay and throughput of ED-TMS are investigated, formulated, and analyzed. Simulation and numerical results are addressed in Section 6. Finally, Section 7 draws the conclusion and future work.

2. WBAN architecture

There are many sensors uniformly distributed around the body to monitor the health status, and each of the sensors gathered and sent data to the master node (MN). Where a WBAN that is based on the single-hop star topology, all the sensors send their data directly to the MN. The MN, then, send its data to the monitor node, which either analyze the received data or forward the data over the Internet to the hospital or doctors. Figure 1 (a) shows an example of a traditional WBAN system.

In the WBANs, it should consider a number of physical environments, due to the networks are configured on/in the body. Where the sensors are attached to the human body which is mobile that make the sensors owing numerous body movements. Therefore, the distances between the sensors and MN are varying. Some sensors may have a large distance or weak link to the MN, and thus, transporting the data sufficiently to the MN in a single hop is difficult.

A CC is considered one of the best solutions to overcome the aforementioned problem, i.e., single-hop transmission. Various CC modes are widely inspected in the literature. However, the ICC is considered in this work, and it is summarized as follows: if the MN (or destination) received the data packet correctly from source (S), then it sends an acknowledgment (ACK) to the S and the

![Figure 1. Communication architecture for WBAN sensors: (a) traditional architectures and (b) cooperative communication architectures.](image_url)
relay sensor (R) drops what received from S. Otherwise, it sends a negative acknowledgment (NACK) that allows the R retransmit what was received from the S, but MN drops what received from the S. The cooperative scenario is shown in Figure 1(b). In what follows, the distances from S to MN, S to R, and R to MN are denoted as $d_{sd}$, $d_{sr}$, and $d_{rd}$, respectively, and we denoted link between sensor and MN as $S - D$, link between source and relay sensor as $S - R$, and link between relay sensor to MN as $R - D$.

3. Link and outage probability analysis
In this section, the propagation model, the link analysis, and outage probability over the $S - D$ link are described. The signal-to-noise ratio ($\gamma_{sd}$) of the $S - D$ link can be expressed as:

$$\gamma_{sd} = \frac{P_t \delta_c}{P_N} K_{sd}$$  \hspace{1cm} (1)

where $P_t$ is the transmission power, $\delta_c$ is a multiplication of all antennas’ gain, $P_N$ is the noise power, and $K_{sd}$ is a complex Gaussian random variable with unit variance. Hence, the channel gain $|K_{sd}|^2$ is an exponentially distributed random variable with the mean value, $E [|K_{sd}|^2] = d_{sd}^{-\alpha}$, where $E$ denotes expectation, the $d_{sd}$ is the distance of the $S - D$ link, $\alpha$ is the path loss factor which varies from 2 to 6, which is described as fluctuations of the amplitude of a radio signal at the receiver. The transmission rate over $S - D$ link can be expressed as:

$$\beta_{sd} = B \log_2 \left( 1 + \frac{P_t \delta_c}{P_N} K_{sd} \right)$$ \hspace{1cm} (2)

where $B$ is the transmission channel bandwidth and is set to unity. The outage probability is defined as the probability that the transmission rate is less than or equal the required transmission rate $\beta_o$. The outage probability can be expressed as (Ibrahim et al., 2008):

$$p_{out}^{sd} = P(\beta_{sd} \leq \beta_o) = 1 - \exp \left( - \frac{U_d}{P_t d_{sd}^{\alpha}} \right)$$ \hspace{1cm} (3)

where $U_d = P_N \left( 2^{\delta_c} - 1 \right) / \delta_c$. Consequently, the successful transmission probability of the $S - D$ link can be expressed as:

$$p_{sd}^{s} = 1 - p_{out}^{sd} = \exp \left( - \frac{U_d}{P_t d_{sd}^{\alpha}} \right)$$ \hspace{1cm} (4)

4. Reliable emergency data transmission using transmission mode selection

4.1. Proposed method description
In this paper, it has been proposed an efficient protocol to transmit emergency data reliably for WBAN, named as Emergency Data Transmission using Transmission Mode Selection (ED-TMS). The proposed protocol work in a cooperative fashion by considering emergency data and utilizing the principle of the automatic repeat request (ARQ). The ED-TMS has two events, and it is summarized as follows:

(1) The first event is Emergency Data Event (denoted as $X$), and it occurs when data gathered by the sensor are critical and it should be transmitted for the destination efficiently. In such case, critical data transmitted either through a direct path, which is a source to the destination, or through the relay path, which is the source to relay and then relay to the destination.

(2) The second event is Normal Data Event (denoted as $Y$), and it occurs when gathered data by the sensor are normal or not critical and it could be transmitted directly to the destination without the need to the relay path.
4.2. Formulation of the ED-TMS

As described earlier, the ED-TMS comprises two events, and it is mathematically expressed as

\[ P_{ED-TMS} = P(X) + P(Y) \]  

where \( P(X) \) is the probability of the gathered data was critical. The critical data transmitted through either the direct path or the relay path, and it is mathematically expressed as

\[ P(X) = CI \cdot P_{coop} \]  

where the \( CI \) is the critical data index, and it is mathematically expressed as

\[ CI = 1 - \frac{\xi_{\text{min}} - \xi_{\text{max}}}{\xi_{\text{max}}} \]  

where \(|.|\) is the absolute notation, \( \xi_{\text{max}} \) is the maximum critical data index and it equals to 7, and \( \xi_{\text{min}} \) is the minimum critical data index and it varies between 0 and 7. Therefore, \( CI \) varies between 0 and 1. Where \( \xi_{\text{min}} \) depends on the gathered data from the human body, if the data are critical, then \( \xi_{\text{min}} \) is high and vice versa. Table 2 shows the probability of the critical data index with a different value of \( \xi_{\text{min}} \).

The \( P_{\text{coop}}^c = \left( 1 - P_{\text{out}}^\text{coop} \right) \) is the successful transmission probability of the cooperative transmission mode with RS, and it can be expressed as:

\[ p_{\text{out}}^\text{coop} = p_{\text{out}}^{\text{sd}} \cdot p_{\text{out}}^{\text{sr}} + \left( 1 - p_{\text{out}}^{\text{sr}} \right) p_{\text{out}}^{\text{sd}} \cdot p_{\text{out}}^{\text{rd}} \left( 1 - P_o \right) \]  

where \( p_{\text{out}}^{\text{sd}}, p_{\text{out}}^{\text{sr}}, \) and \( p_{\text{out}}^{\text{rd}} \) represent \( S-D, S-R \), and \( R-D \) links that are in the outage. In addition, \( P_o \) is the probability of the \( S-D \) link greater than the maximum of the minimum of the \( S-R \) and \( R-D \) links, and it can be expressed as:

\[ P_o = P(K_{sd} > K_{sr}^{\text{max}}) = 1 - P(K_{sr}^{\text{max}} > K_{sd}) \]  

then,

\[ K_{sr}^{\text{max}} = \arg\max_k \min\{K_{sr}, K_{rd} \} \]  

where \( K_{sr}^{\text{max}} \) is the selected relay index in conventional relay networks over \( k \) potential relays, and \( K_{sr} \) and \( K_{rd} \) are random variables of \( S-R \) and \( R-D \) links, respectively. Thus, the relay is chosen based on the channel gains of the relaying links. In the sequel, the

| \( \xi_{\text{min}} \) | \( \xi_{\text{max}} \) | \( CI \) |
|---|---|---|
| 0 | 7 | 0 |
| 1 | 7 | 0.857 |
| 2 | 7 | 0.714 |
| 3 | 7 | 0.571 |
| 4 | 7 | 0.428 |
| 5 | 7 | 0.285 |
| 6 | 7 | 0.142 |
| 7 | 7 | 1.0 |
cumulative distribution function of two independent random variables can be expressed as:

\[ P_o = 1 - \left( \exp(-d_{sd} K_{sd}) \cdot \exp(-d_{rd} K_{rd}) \right) \quad (11) \]

Taking the average of \( P_o \) over \( K_{sd} \), thus the average of the \( P_o \) is expressed as:

\[
P_o = 1 - \int_0^\infty \left( \frac{1}{d_{sd} + \frac{1}{d_{rd}}} \right) \left( \frac{1}{d_{sd}} \right) \exp\left(-\frac{1}{d_{sd}} K_{sd}\right) dK_{sd},
\]
\[
= 1 - \left( 1 + \frac{d_{sd}}{d_{rd}} \right)^{-1}.
\]
\[
\quad \text{the } 1 - x \approx \exp(-x), \text{ then re-write Equation (12) as}
\]
\[
P_o \approx \exp\left(-\left(1 + \frac{d_{sd}}{d_{rd}} + \frac{d_{rd}}{d_{sd}}\right)^{-1}\right)
\]
\[
\quad \text{with the help of Equation (3), substitute Equation (13) in Equation (8), we obtain } P_{\text{out}}^\text{coop} \text{ as}
\]
\[
P_{\text{out}}^\text{coop} = 1 - \left( 1 - \exp\left(-\frac{U_l}{P_t d_{sd}}\right) \right) \cdot \left( 1 - \exp\left(-\frac{U_l}{P_t d_{rd}}\right) \right) \cdot \exp\left(-\left(1 + \frac{d_{sd}}{d_{rd}} + \frac{d_{rd}}{d_{sd}}\right)^{-1}\right)
\]
\[
+ \exp\left(-\frac{U_l}{P_t d_{sd}}\right) \left( 1 - \exp\left(-\frac{U_l}{P_t d_{sd}}\right) \right) \cdot \exp\left(-\left(1 + \frac{d_{sd}}{d_{rd}} + \frac{d_{rd}}{d_{sd}}\right)^{-1}\right)
\]
\[
\quad \text{then, substitute Equations (7) and (14) in Equation (6), we obtain emergency data event } P(X) \text{ as}
\]
\[
P(X) = \left(1 - \frac{\xi_{\text{min}} - \xi_{\text{max}}}{\xi_{\text{max}} - \xi_{\text{min}}} \right) \cdot \left[ 1 - \left( 1 - \exp\left(-\frac{U_l}{P_t d_{sd}}\right) \right) \cdot \left( 1 - \exp\left(-\frac{U_l}{P_t d_{rd}}\right) \right) \cdot \exp\left(-\left(1 + \frac{d_{sd}}{d_{rd}} + \frac{d_{rd}}{d_{sd}}\right)^{-1}\right)
\]
\[
+ \exp\left(-\frac{U_l}{P_t d_{sd}}\right) \left( 1 - \exp\left(-\frac{U_l}{P_t d_{sd}}\right) \right) \cdot \exp\left(-\left(1 + \frac{d_{sd}}{d_{rd}} + \frac{d_{rd}}{d_{sd}}\right)^{-1}\right)
\]
\[
\quad \left( 1 - \exp\left(-\frac{U_l}{P_t d_{sd}}\right) \right) \left( 1 - \exp\left(-\left(1 + \frac{d_{sd}}{d_{rd}} + \frac{d_{rd}}{d_{sd}}\right)^{-1}\right) \right)
\]
\[
\quad \text{In what follows, nonemergency data event is } P(Y), \text{ and it is given as}
\]
\[
P(Y) = (1 - CI) \cdot (1 - P_{\text{out}}^\text{coop})
\]
\[
\quad \text{Finally, substitute Equations (16) and (15) in Equation (5), we obtain the ED-TMS probability.}
5. Delay and throughput analysis of ED-TMS

5.1. Delay analysis of ED-TMS in WBAN

The average end-to-end delay of the protocol IEEE 802.15.6 of ED-TMS is evaluated in this subsection. Where the average end-to-end delay is defined as the total time required of the medium access delay to transmit data and includes average contention time due to collision \((T_C)\), the average successful transmission time with no collision and no fading \((T_{suc})\), and average failure time due to fading but no collision \((T_{fail})\) (Khalid, Wang, Ra, & Sankar, 2011).

\[
T_{e2e} = T_C + T_{suc} + T_{fail}
\]  
\[\text{(17)}\]

average contention time due to collision can be expressed as:

\[
T_C = T_{data} + T_{CW} + T_{ACK} + 2T_{SIFS} + 2T_a
\]  
\[\text{(18)}\]

where \(T_{act}\) is the RF activity time, which can be expressed as:

\[
T_{act} = T_{on} + T_{CW} + T_{data} + T_{ACK} + 2T_{SIFS} + 2T_a
\]  
\[\text{(19)}\]

the transmission time required for \(\text{ACK}\) can be expressed as:

\[
T_{ACK} = T_P + T_{PHY} + T_{MAC} + T_{FCS}
\]  
\[\text{(20)}\]

Average successful transmission time with no collision and no fading can be expressed as

\[
T_{suc} = CI \left( T_{sd}^{rd} \frac{P_s}{P_d} + \left( T_{sd}^{rd} + T_{sd}^{d} \right) \left( 1 \left( 1 - P_s \right) P_s \frac{P_r}{P_d} \right) \right) \left( 1 - CI \right) P_s T_{sd}^d T_{act}
\]  
\[\text{(23)}\]

Equation (23) comprises two terms. The first term is end-to-end required time of the transmission when the data gathered by the source were critical, which are transmitted via CC including RS. The second term is end-to-end required time of the transmission when the gathered data by the sensor were not critical, which are always transmitted over DTM.

It is clear from Equation (23) that as the CI approaches to 1, then either \(T_{sd}^{rd}\) is the required time to transmit the data or \(T_{sd}^{rd} + T_{sd}^{d}\) is the required time to transmit the data to the destination. However, as the CI approaches to zero, then \(T_{sd}^{rd}\) is the required time to transmit the data to the destination. \(T_{sd}^{rd}\) are the RF activity time of the relay sensor to serve source sensor data retransmission and it is equal to \(T_{sd}^{rd}\). Finally, the average failure time due to fading but no collision can be expressed as

\[
T_{fail} = (1 - P_s^{rd}) (1 - P_s^{p}) P_s^{p} P_r^{p} T_{sd}^{rd} T_{act}
\]

+ \(1 - P_s\) \left( T_{sd}^{rd} + T_{sd}^{d} \right) \left( 1 - P_s \right) P_s \left( 1 - P_r \right) P_s^{p} + \left( 1 - P_s \right) \left( 1 - P_r \right) \left( 1 - P_s^{p} \right) \left( 1 - P_r^{p} \right) T_{sd}^{rd} T_{act}
\]  
\[\text{(24)}\]

It is clear from Equation (24) that the first term corresponds to the events when the \(S - D\) and \(S - R\) links in the outage, while \(R - D\) link not in the outage. The second term corresponds to the events when the \(S - D\) and \(R - D\) links in the outage, while \(S - R\) link not in the outage. The last term corresponds to the events when the \(S - D\), \(S - R\), and \(S - D\) links in the outage. In Equation (24), we did not include the CI because channel fading does not affect by the types of the gathered data whether it is critical or not.
The transmission rate of the PHY, MAC headers, and payload is depending on the channel condition between nodes (Liu, Tao, Narayanan, Korakis, & Panwar, 2007). The rate with ED-TMS can be expressed as

\[ R_{\text{rate}} = C_1 P_{\text{coop}} R_{\text{max}} + (1 - C_1) P_{\text{id}} R_{\text{max}} \]  

(25)

Where \( R_{\text{max}} \) is the maximum transmission rate of IEEE 802.15.6 standard and it is 75.9 Kbps for DPSK modulation. The following abbreviation and acronyms are used for the above times.

### 5.2. Throughput analysis of ED-TMS in WBAN

In this section, the throughput of the proposed protocol has been analyzed and formulated. The throughput between \( i \) and \( j \) nodes of ED-TMS is defined as the number of successfully transmitted bits per second, and it can be expressed as (Jang, Kim, & Wie, 2012):

\[ \eta_{\text{ED-TMS}} = \frac{P_{\text{acc}} P_{\text{ED-TMS}} E(P)}{P_{\text{idle}} T_s + P_{\text{acc}} T_{\text{idle}} + (1 - P_{\text{acc}} - P_{\text{idle}}) T_c} R_{\text{max}} \text{ [bps]} \]  

(26)

where \( E(P) \) is the transmission time for the payload bits and \( P_{\text{acc}} \) is the probability that just one sensor node accesses a given slot and it is given as (Khalid et al., 2011):

\[ P_{\text{acc}} = N \tau (1 - \tau)^{N-1} \]  

(27)

where \( \tau \) is the probability that each sensor node randomly and independently accesses a slot time, and it depends on the probability of packet loss, but latterly, we found optimum value of \( \tau \), and \( N \) is the number of nodes. \( P_{\text{idle}} \) is the probability that no sensor node accesses the slot and it is given as (Khalid et al., 2011):

\[ P_{\text{idle}} = (1 - \tau)^N \]  

(28)

where the throughput shown in Equation (26) is maximized as the term shown below is minimized

\[ f(\tau) = \frac{P_{\text{idle}} T_s + P_{\text{acc}} T_{\text{idle}} + (1 - P_{\text{acc}} - P_{\text{idle}}) T_c}{P_{\text{acc}} P_{\text{ED-TMS}}} \]  

(29)

We deleted the term that is not included \( \tau \), then re-write Equation (29) as

\[ f(\tau) = \frac{P_{\text{idle}} (T_s - T_c) + T_c}{P_{\text{acc}} P_{\text{ED-TMS}}} \]  

(30)

The optimum of \( \tau \) that could maximize the throughput is obtained by derivative Equation (30) with respect to \( \tau \)

\[ (1 - \tau_{\text{op}})^N - \frac{T_c}{T_s} N \tau_{\text{op}} + \frac{T_c}{T_s} (1 - (1 - \tau_{\text{op}})^N) = 0 \]  

(31)

For a small value of \( \tau \), we can obtain \( (1 - \tau_{\text{op}})^N \) as

\[ (1 - \tau_{\text{op}})^N \approx 1 - N \tau_{\text{op}} - \frac{N(N - 1)}{2} \tau_{\text{op}}^2 \]  

(32)
Finally, insert Equation (32) in Equation (31), we obtain $\tau_{op}$ as

$$\tau_{op} = \frac{1}{N} \left( 1 + \frac{T_s}{T_s} \right)^{-1}$$

(33)

6. Simulation and results discussion

In this section, the performance of the ED-TMS protocol that is presented in the aforementioned sections has been evaluated in terms of successful transmission probability, end-to-end delay, and throughput. In the simulation, random topology has been considered, where sensors are randomly distributed in 3.5 \times 3.5 square area (in meter) and a number of the sensors are fixed in this area. The destination is located at the origin (0, 0), and correspondence source sensor located at $(d_{sd}, 0)$. In addition, the number of relay sensors is varying and randomly deployed between source and destination. The numerical parameter used in this paper is given in Table 3. The pseudo code of the proposed protocol is shown in Table 4.

Figure 2 shows the comparison of outage probability of the DTM and ED-TMS protocol for the different internode distance $S - D$ link. The outage probabilities decrease as the distance $S - D$ link decreases, and we can also note that the outage probabilities of the ED-TMS are better than the outage probability of the DTM. In addition, the outage probability of the ED-TMS with RS is better than outage probability of ED-TMS without RS. At 1.8 m, the outage probability reductions of ED-TMS with RS with respect to ED-TMS without RS and DTM are 50% and 99%, respectively. On the other hand, the outage probability reduction of ED-TMS without RS with respect to DTM is 98%.

Figure 3 shows the comparison of successful transmission probability of the DTM and ED-TMS protocol for different internode distance $S - D$ link. The successful transmission probabilities at all distance are approximately the same. We can see from Figure 3 that, at large distance, the successful transmission probability of the ED-TMS with RS is better than DTM and ED-TMS without RS, respectively. At 2.9 m, the successful transmission probability improvements of ED-TMS with RS with respect to ED-TMS without RS and DTM are 2% and 18.5%, respectively. On the other hand, successful transmission probability improvement of ED-TMS without RS with respect to DTM is 17%.

Figure 4 shows the comparison of successful transmission probability of the ED-TMS protocol for different critical data index values of $\xi_{min}$. As the $\xi_{min}$ increases, the required successful

| Table 3. Numerical parameters |
|--------------------------------|
| Frequency band [MHz] | 402 – 405 |
| Bandwidth [MHz] | 0.3 |
| Maximum transmission rate ($R$) [Kbps] | 75.9 |
| Modulation | DPSK |
| Payload size [bits] | 2000 |
| Minimum contention windows CWmin [slots] | 16 |
| Maximum contention windows CWmax [slots] | 64 |
| Clear channel assessment [bits] | 63 |
| MAC header [bits] | 56 |
| MAC footer [bits] | 16 |
| Short interframe spacing time TpSIFS [µs] | 50 |
| Preamble [bits] | 88 |
| Slot time Ts [µs] | 125 |
| Delay time $\alpha$ [µs] | 1 |
| Maximum critical data index $\xi_{max}$ | 7 |
| Number of nodes | 4 |
Table 4. ED-TMS pseudo code

Require: $P_t$, $U_t$, $C_{max}$, $d_{sd}$, and $Pra = \text{random}(1, \text{length}(d_{sd}))$.

begin

01 For generated packet $n$

02 Select $C_{min} \in \text{random}[0, 7]$

03 Select $d_{id} = [0.1 : 0.1 : 3.5]$

04 for $v = 1 : 1 : \text{length}(d_{sd})$

05 $d_u = Pra(v) \times d_{sd}(v)$

06 $d_d = Pra(v) \times d_{sd}(v)$

07 Calculate back-off time given in (22)

08 Calculate successful transmission probability given in (5)

09 Calculate $R_{av}$ given in (25)

10 Calculate time for each transmitted packet or frame as

11 $T_y = \text{number of bits of } y \times \frac{R_{av}}{R}$

12 Calculate end-to-end delay given in (17) as function of $d_{sd}(v)$

13 Calculate throughput given in (26) as function of $d_{sd}(v)$

14 Endfor

15 Endfor

Figure 2. Comparison of outage probability of DTM and ED-TMS with internode distance of $S-D$ link, $\alpha$ is 4, $P_N = 5$, and $\delta_c = 5$. 
Figure 3. Comparison of successful transmission probability of DTM and ED-TMS with internode distance of $S-D$ link, the $\alpha = 4$, $P_n = 3$, $\delta_c = 5$ and $\zeta_{min} = 4$.

Figure 4. Successful transmission probability of ED-TMS with $\zeta_{min}$. The internode distance 2.5 m of $S-D$ link, the $\alpha$ is 5, $P_n = 5$, and $\delta_c = 5$. 
transmission probability increases as well, in order to transmit the critical data efficiently over the wireless medium. We can also notice that the successful transmission probability of the ED-TMS with RS is better than ED-TMS by 6%.

Figure 5 shows the comparison of end-to-end delay of the DTM, MI-ICC, and ED-TMS protocol for different internode distance $S - D$ link. At a small distance, the performance of the ED-TMS without RS, DTM, and MI-ICC is approximately the same, while the ED-TMS with RS has a less end-to-end delay. The end-to-end delay of ED-TMS without RS at large distance is less than DTM and MI-ICC. At 3.4 m, the end-to-end delay reduction of ED-TMS with RS with respect to DTM, MI-ICC, and ED-TMS without RS are 24.5%, 28%, and 30%, respectively.

Figure 6 shows the comparison of end-to-end delay of ED-TMS protocol for different critical data index values of $\zeta_{min}$. Similar to Figure 4, we can observe the end-to-end of ED-TMS with RS is better than ED-TMS without RS. In addition, as the $\zeta_{min}$ increases, the end-to-end delay increases as well.

Figure 7 shows the comparison of throughput of the DTM, MI-ICC, and ED-TMS protocol for different internode distance $S - D$ link. At a small distance, the performance of the ED-TMS without RS, DTM, and MI-ICC is approximately the same, while the ED-TMS with RS has better throughput. At 3.4 m, the throughput improvement of ED-TMS with RS with respect to DTM, MI-ICC, and ED-TMS without RS are 14.5%, 6%, and 5%, respectively. Figure 8 shows the comparison of the throughput of ED-TMS protocol for different critical data index values of $\zeta_{min}$. The ED-TMS with RS improved the throughput with respect to ED-TMS without RS.

7. Conclusion
In this paper, we have proposed a novel CC aware types of gathered data based on IEEE 802.15.6 CSMA policy under Rayleigh fading channel, namely ED-TMS, for WBAN. We have also proposed a
Figure 6. End-to-end delay of ED-TMS with $\zeta_{\text{min}}$. The internode distance 3 m of $S-D$ link, the $a$ is 5, $P_n = 3$, and $\delta = 5$.

Figure 7. Comparison of throughput of DTM and ED-TMS with internode distance of $S-D$ link, $a$ is 4, $P_n = 3$, $\delta = 5$, and $\zeta_{\text{min}} = 6$. 
new RS strategy along with ED-TMS. The proposed protocol increased the probability of a successful transmission if the gathered data were critical, by selecting either the direct path or the relay path, while, if the gathered data were not critical, the data transmitted over the direct path. We have demonstrated that the ED-TMS can substantially enhance the successful transmission, reduced end-to-end delay, and enhanced throughput compared to DTM IEEE 802.15.6 CSMA and MI-ICC. As a future work, we will design and investigate MAC protocol for inter-WBAN cooperation.

Figure 8. Throughput of ED-TMS with $\eta_{\text{crit}}$. The internode distance $2 \text{m of } S-D$ link, the $a$ is $5$, $P_N = 3$, and $\delta = 5$.

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