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Medium access control protocol based on time division multiple access scheme for wireless body area network

Wan Haszerila Wan Hassan[1,2], Darmawaty Mohd Ali[1], Juwita Mohd Sultan[2], Murizah Kassim[3]
[1]Wireless Communication Technology Group, School of Electrical Engineering, College of Engineering, Universiti Teknologi MARA, Shah Alam, Malaysia
[2]Fakulti Teknologi dan Kejuruteraan Elektronik dan Komputer, Universiti Teknikal Malaysia Melaka, Melaka, Malaysia
[3]Institute for Big Data Analytics and Artificial Intelligence, Universiti Teknologi MARA, Shah Alam, Malaysia

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ABSTRACT

In recent years, the demand for wireless body area network (WBAN) technology has increased, driven by advancements in medical and healthcare applications. WBAN consists of small, low-power, and heterogeneous sensor devices attached inside or outside the body for continuous health monitoring. Medium access control (MAC) is pivotal in addressing WBAN challenges by ensuring reliability and energy efficiency under a dynamic environment caused by body movement. Therefore, to tackle these challenges, this paper presents a MAC protocol based on time division multiple access (TDMA) to enhance the WBAN performance. The proposed TDMA-MAC protocol employs a one-periodic scheduled-based access method to provide reliable data transmission while satisfying the WBAN requirements. The proposed protocol is compared to the IEEE 802.15.6 MAC, enhanced packet scheduling algorithm MAC (EPSA-MAC), and concurrent MAC (C-MAC) protocols based on the performance metrics of packet delivery ratio (PDR), network throughput, energy consumption, and average delay. The simulation results show that the TDMA-MAC protocol outperforms its competitors as it could achieve up to 98% PDR, 30% enhanced throughput, 30% energy optimization, and 20% improvement in average delay.

Corresponding Author:

Darmawaty Mohd Ali
Wireless Communication Technology Group, School of Electrical Engineering, College of Engineering, Universiti Teknologi MARA
40450 Shah Alam, Selangor, Malaysia
Email: darma504@uitm.edu.my

1. INTRODUCTION

The wireless body area network (WBAN) has allowed the development of low-cost e-healthcare and well-being applications [1], [2]. In contrast to the wireless sensor network (WSN), the WBAN introduces new challenges and features, replacing wired and complex healthcare equipment, thereby allowing continuous monitoring of crucial data while limiting the user's mobility [3]–[5]. The performance of WBAN relies on the design of medium access control (MAC) protocols [6], [7]. In WBAN communication, MAC protocols are categorized into contention-based, scheduled-based, and hybrid-based access methods [8], [9]. The carrier-sense multiple access with collision avoidance (CSMA/CA) represents a contention-based scheme, whereas time division multiple access (TDMA) is adopted as a scheduled-based scheme [10]. Meanwhile, the hybrid-based combines a schedule-based scheme with a contention-based scheme to leverage the advantages of both techniques [11], [12]. A scheduled-based scheme outperforms a contention-based approach in a star topology network [13], [14]. Because of the limited communication space in WBAN, it operates within short ranges. Thus, using a multi-hop network is unnecessary due to the limited number of sensor devices. As a result, WBAN often adopts a star topology network [15]. In scheduled-based MAC protocols, the sensor nodes follow a schedule when accessing the communication channel. Each sensor node is idle at the time slots allocated to others and only uses the channel at designated time slots [16].

Numerous MAC protocols have been developed to address WBAN requirements, enhance energy efficiency, and manage communication failures. Several scheduled-based methods are proposed in [17]–[23] to provide better solutions for WBAN. Salayma *et al.* [17] presents two scheduling approaches, which are dynamic scheduling based on sleeping slots (DSBS) and dynamic scheduling based on buffer (DSBB). Another technique in [18] utilizes the WBAN communication channel conditions to adjust scheduled slot allocation, aiming to address interference and minimize power consumption. In study [19], a dynamic scheduling slots (DSS) method for optimizing slots scheduling using a temporal autocorrelation model is proposed. Realistic on-body data is utilized to investigate the autocorrelation of the wireless channels using customized wireless transceivers. Ambigavathi and Sridharan [20] develop an enhanced packet scheduling algorithm MAC (EPSA-MAC) protocol based on IEEE 802.15.4 that dynamically assigns time slots for body sensor nodes. A dynamic allocation scheme of scheduled slots for the beacon mode with superframe boundaries of the IEEE 802.15.6 standard is proposed in [21]. The study in [22] presents a MAC protocol based on the IEEE 802.15.4 standard, incorporating dynamic slot allocation to accommodate the varying rates of heterogeneous data traffic sensed by various sensor nodes. The work in [23] develops a joint throughput channel aware (TCA) dynamic scheduling algorithm for the IEEE 802.15.6 standard, which exploits the *m*-periodic scheduling techniques for variable traffic. Furthermore, the studies in [24], [25] present MAC protocol using contention-based methods. Ambigavathi and Sridharan [24] suggests a MAC protocol employing CSMA/CA based on the IEEE 802.15.6 standard to minimize the transmission delay of critical data packets and resolve conflicts among other priority sensor nodes during the back-off phases. Additionally, Zhang *et al.* [25] develops an IEEE 802.15.6 CSMA/CA, called concurrent MAC (C-MAC) protocol, incorporating an asynchronous duty cycling mechanism. It employs an ordering-based communication scheme to eliminate packet collisions. However, prioritizing multiple sensor devices leads to higher collisions during channel access.

This paper proposes a novel TDMA-MAC protocol based on beacon mode with a beacon period of the IEEE 802.15.6 standard. The proposed method utilizes a one-periodic scheduled-based access technique in the contention-free period to ensure efficient, fast and reliable data transmission in WBAN communication. Besides, it can overcome the limitations inherent in the contention-based method by enhancing reliability and energy-saving whilst boosting the overall WBAN performance. The key contribution of the proposed protocol is mitigating the issues associated with contention-based methods, such as packet collisions, idle listening, and overhearing, which result in high energy dissipation and performance degradation.

2. METHOD

Figure 1 shows the superframe structure of the proposed MAC protocol, which is comprised of a beacon (B), a random-access phase (RAP), and a scheduled access phase (SAP). For the establishment of the superframe structures, the minimum slots for contention-based access must be specified before the contention-free time begins, as suggested by task group 6 (TG6) [26]. Aligned with this recommendation, Salayma *et al.* [17] indicates that, for effective WBAN operation, the RAP slots should be allocated with a minimum of two time slots. Accordingly, the proposed MAC protocol incorporates two time slots for RAP and functions as a contention-based period to ensure the successful operation of the WBAN. Meanwhile, the SAP is assigned with 30-time slots and operates as a scheduled-based period.

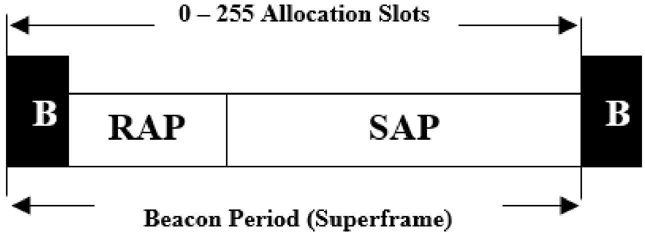

Figure 1. Proposed superframe structure of TDMA-MAC protocol

Before initiating the data transmission process, the sensor nodes perform connection requests (CR) and connection assignment (CA) procedures to integrate into the communication network during the RAP slots. Therefore, the TDMA-MAC protocol allocates RAP slots to handle the connection procedure process. The data transmission begins when the sensor nodes connect to the network. Each sensor node transmits data packets at designated time slots and remains in a sleep state during the time slots allocated to other sensor nodes. The time duration for successful data frames transmission, T_s can be written as in (1), where T_{SIFS} is the short inter frame duration and T_{ACK} is the time duration of the acknowledgment (ACK) frame.

$$T_s = T_{Data} + 2 * T_{SIFS} + T_{ACK} \quad (1)$$

Figure 2 describes the flowchart of the TDMA-MAC protocol. The coordinator broadcast beacon frames to all sensor nodes within the communication network to achieve node clock synchronization. After synchronization, each unconnected sensor node must establish a connection with the network coordinator before initiating the data transmission process. In this procedure, the unconnected sensor nodes transmit a CR frame to the coordinator, utilizing a contention-based scheme within the RAP slots. At this stage, the unconnected sensor nodes are lacking their scheduled allocation. Subsequently, the sensor nodes await the reception of the CA frame or immediate acknowledgment (I_ACK) from the coordinator. Upon receiving the I_ACK frame, the coordinator records the assigned slots number for receiving data from the sensor nodes during their designated slots intervals. Once the sensor nodes are integrated into the WBAN, they commence data transmission based on their scheduled slots. If the SAP exceeds zero, the designated sensor node transitions from MAC_STATE to MAC_FREE_TX (scheduled). The sensor node is allocated for scheduled free time access throughout this time frame, allowing it to transmit freely and wait for I_ACK. The reception of the I_ACK implies that the sensor node has successfully transmitted the slots. Conversely, the sensor nodes move from MAC_STATE to MAC_SLEEP, allowing them to go to sleeping mode until the sleeping period expires to save energy consumption.

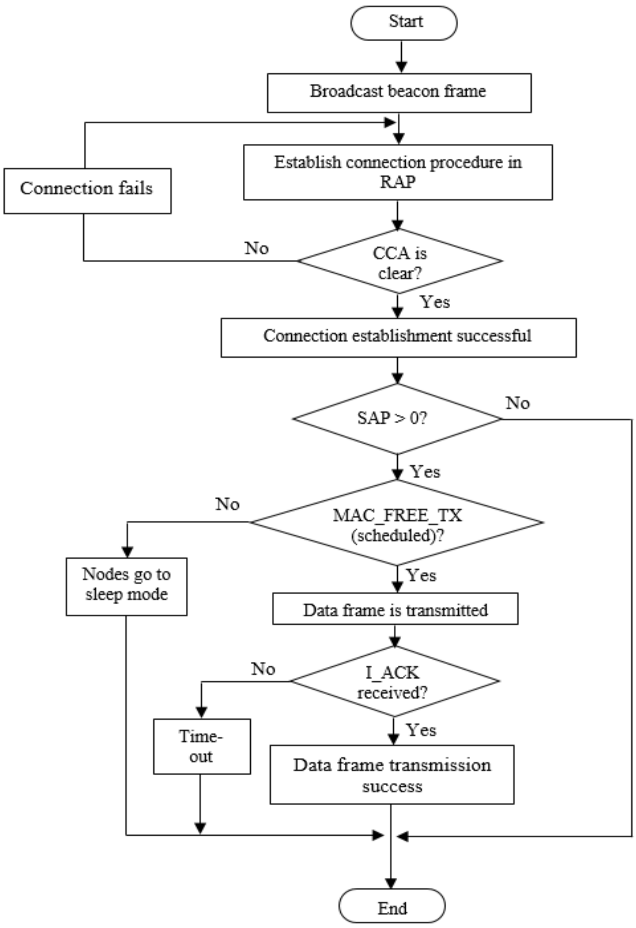

Figure 2. Flowchart of TDMA-MAC protocol

The performance of the proposed MAC protocol is simulated using Castalia-3.3 based on OMNeT++4.6. The simulation parameters, which adhere to the IEEE 802.15.6 specifications, are presented in Table 1. The network utilizes a star topology comprising one network coordinator (hub) and five sensor nodes. The simulated network topology is depicted in Figure 3, allowing for a direct link between each sensor node and the network coordinator and single-hop data transmission. The proposed protocol adopts a configuration of 30-time slots for a scheduled access scheme. Thus, each sensor node is allocated with six time slots once the network is established.

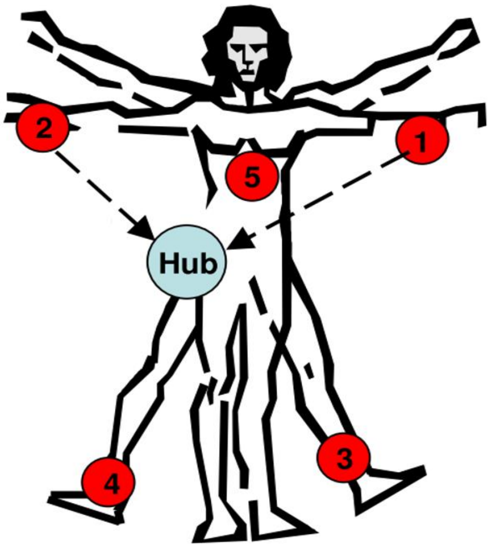

Figure 3. Single-hop star topology network

Table 1. Simulation parameters

Parameter	Value
Simulation time	200 s
Number of nodes	6
Packet rate	5 packets/s
Contention size	0.36 ms
Slot allocation size	10 ms
Beacon period	32 slots
RAP size	2 slots
SAP size	30 slots
pTIFS	0.03 ms
Transmission rate	1,024 kbps

3. RESULTS AND DISCUSSION

This section examines the performance of the proposed TDMA-MAC protocol in the WBAN. This section focuses on packet delivery ratio (PDR), throughput, energy consumption, and average delay. A comparative assessment is conducted between the performance of the proposed TDMA-MAC protocol against IEEE 802.15.6 MAC [5], EPSA-MAC [20], and C-MAC [25] protocols.

3.1. Packet delivery ratio

The reliability of the MAC protocol is analyzed by measuring the PDR in the network. The higher the value of PDR, the better the performance of the MAC protocol. The PDR is the ratio of the total number of packets the network coordinator receives to the total number of packets transmitted by sensor nodes. The PDR of all MAC protocols are given in Figure 4. The result shows that the TDMA-MAC protocol can achieve a PDR of around 98% across various simulation times. This result represents an enhancement of up to 20% compared to its counterparts. The improvement is attributed to the scheduled-based method employed by the TDMA-MAC protocol, which enables each sensor node to utilize the channels during specific time slots and turn to sleep mode when the time slots are allocated to other sensor nodes. The scheduling approach reduces the likelihood of collisions and contention, contributing to a more reliable and predictable network performance. Further, the proposed TDMA-MAC protocol anticipates the status of the WBAN channel, effectively. This capability stems from the scheduled operation of sensor nodes using the TDMA approach. In doing so, the primary reason for packet loss in the TDMA-MAC protocol is the occurrence of deep fades in their links with the network coordinator. In addition, the EPSA-MAC protocol demonstrates a PDR above 80%, which is inferior to the proposed TDMA-MAC protocol. Despite implementing a scheduling method in EPSA-MAC, it exhibits a lower PDR when compared to the TDMA-MAC protocol due to the restricted number of time slots allocated to the sensor nodes. The lower PDR presented in the IEEE 802.15.6 MAC and C-MAC protocols is predominantly due to the contention-based approach. Indeed, the main reason for packet loss is packet collisions and re-transmission, thus contributing to a lower PDR.

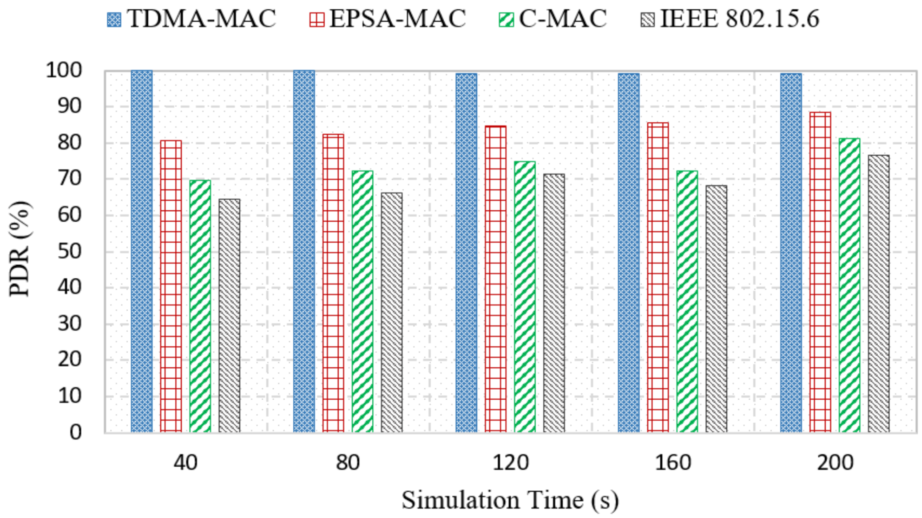

Figure 4. Packet delivery ratio

3.2. Network throughput

The average network throughput is determined by dividing the total number of received packets in bits by the simulation time. Figure 5 shows the average throughput while varying the simulation time. Among all MAC protocols, the TDMA-MAC protocol demonstrates higher and more stable throughput, resulting in a 30% increase compared to the others. The increased throughput of the TDMA-MAC protocol results in improved PDR and network performance. Meanwhile, the IEEE 802.15.6 MAC, EPSA-MAC, and C-MAC protocols maintain the minimum throughput value until the end of simulation time.

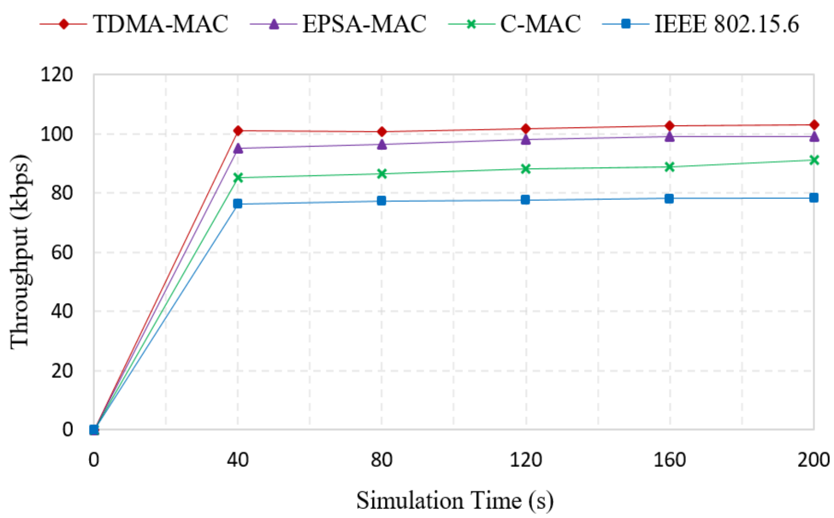

Figure 5. Network throughput

3.3. Energy consumption

The sensor nodes in WBAN are resource constrained. Thus, the lower the energy consumed by the MAC protocols, the better its performance. The total energy consumption by the sensor nodes, E_{total} are calculated as in (2), where E_{tx}, E_{rx}, E_{idle}, and E_{sleep} denote the energy consumed in transmitting, receiving, idle and sleep state.

$$E_{total} = E_{tx} + E_{rx} + E_{idle} + E_{sleep} \quad (2)$$

The energy consumption for all MAC protocols is shown in Figure 6. It can be seen that the proposed protocol consumes less energy compared to its counterparts, which is up to 30% energy optimization. This result is attributed to the effectiveness of scheduled-based techniques, allowing the sensor nodes to conserve energy by entering sleep mode during their inactive time slots, thereby avoiding unnecessary packet collisions and re-transmissions. Furthermore, the time slots allocation tailored to sensor node requirements helps to prevent idle listening. This scenario might arise when sensor nodes are assigned more time slots than required.

Based on this simulation, the energy dissipation of the proposed TDMA MAC protocol may stem from the allocation of two slots in RAP during the contention-based period. On the other hand, the EPSA-MAC protocol demonstrates a slightly higher energy consumption. The EPSA-MAC protocol employs scheduled-based access using IEEE 802.15.4, which consumes more energy and higher bandwidth, leading to performance degradation. Meanwhile, the suboptimal performance is observed in the IEEE 802.15.6 MAC and C-MAC protocols. The increased energy consumption is due to the contention-based scheme. The main shortcoming of the contention-based method is the packet collisions, thus requiring packet re-transmissions and contributing to high energy dissipation. As a result, the proposed TDMA-MAC protocol is more energy-saving and is suitable for low, medium and high data rates in WBAN applications.

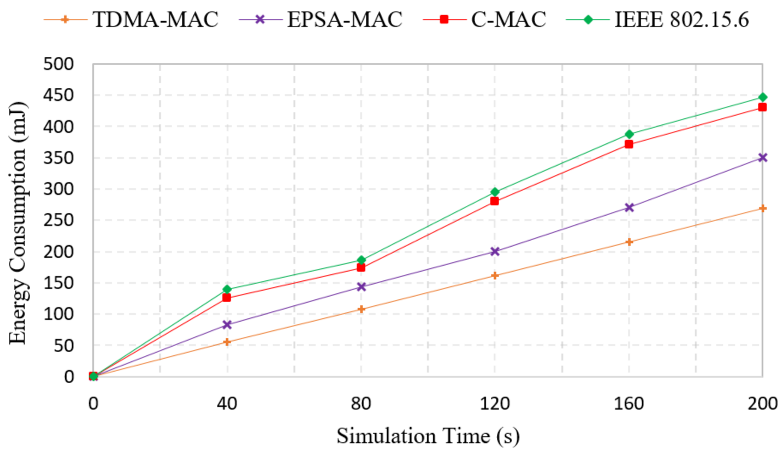

Figure 6. Energy consumption

3.4. Average delay

The high-performance MAC protocol must be delay-efficient to guarantee reliable and fast transmission of critical emergency data. Figure 7 presents the average delay distribution for all MAC protocols, respectively. As seen in this figure, the average delay of the proposed TDMA-MAC protocol is lower than other protocols. The 20% improvement in the average delay is attributed to the dedicated time slots provided to sensor nodes during scheduled access periods, effectively minimizing the delay. Additionally, the scheduled access mechanism ensures predictable and deterministic transmission times, thereby reducing the average delay. The higher delay observed in the EPSA-MAC protocol due to the restricted number of time slots, resulting in inefficient use of available communication channels. The sensor nodes may experience delays in accessing the channel, leading to underutilization of the allocated bandwidth. Conversely, in the C-MAC and IEEE 802.15.6 MAC protocols, the contention process is pivotal in influencing average delay as sensor nodes contend for access to the communication channel. The ensuing collisions and re-transmission process contribute to an increase in the average delay experienced by the protocol.

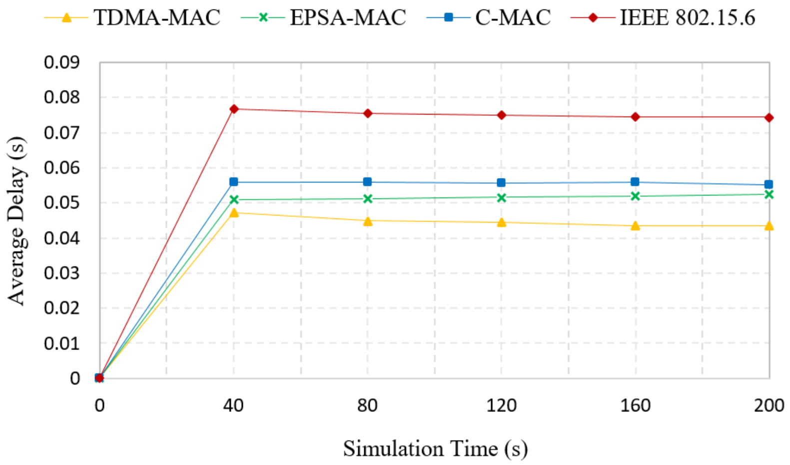

Figure 7. Average delay

4. CONCLUSION

This paper presented a TDMA-MAC protocol developed to improve reliability and energy efficiency in WBAN communication, which is crucial for an effective healthcare monitoring system. By addressing the limitations of contention-based methods, which often lead to WBAN performance degradation due to issues such as high energy dissipation, network delay, contention, packet collisions, idle listening, and overhearing, the proposed TDMA-MAC protocol offers a promising solution. The proposed TDMA-MAC protocol exploits a one-periodic scheduled access technique to mitigate these drawbacks. Additionally, the developed scheme suits WBAN applications because the sensor devices are duty-cycled to access the communication channel. The performance of the TDMA-MAC protocol is evaluated and compared against the IEEE 802.15.6 MAC, EPSA-MAC, and C-MAC protocols. Simulation results demonstrated that the TDMA-MAC protocol outperforms its counterparts regarding PDR, network throughput, energy consumption, and average delay. The IEEE 802.15.6 MAC and C-MAC protocols utilize a contention access method, which presents inherent shortcomings. Conversely, the EPSA-MAC protocol employs a scheduled access scheme based on IEEE 802.15.4, resulting in performance degradation. The future extension of this study is to explore dynamic scheduled slot allocation to tackle the challenges posed by deep fading. By mitigating the impacts of deep fade, such as packet loss rates, and reducing energy wastage, the advanced work has the potential to enhance the quality of services (QoS) and efficiency of WBAN.

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BIOGRAPHIES OF AUTHORS

Wan Haszerila Wan Hassan is a Ph.D. student from the School of Electrical Engineering, College of Engineering, Universiti Teknologi MARA (UiTM). She obtained her master's degree of electrical, electronic and telecommunication engineering and first degree of electrical and electronic engineering from University Teknologi Malaysia (UTM). She can be contacted at email: haszerila@utem.edu.my.

Darmawaty Mohd Ali is an associate professor at the School of Electrical Engineering, College of Engineering, Universiti Teknologi MARA (UiTM). In 2012, she was awarded a PhD Degree from Universiti Malaya (UM). She received her first degree from Universiti Kebangsaan Malaysia (UKM), with honors, in electrical, electronic and system, graduating in 1999. She started her first job as a product engineer before furthering her study for her masters' degree at University Teknologi Malaysia (UTM). Her research interest includes wireless access technology and QoS provisioning in wireless network. She can be contacted at email: darma504@uitm.edu.my.

Juwita Mohd Sultan is a senior lecturer at Universiti Teknikal Malaysia Melaka (UTeM). In 2016, she was awarded a PhD degree in electronic engineering. She received her first degree from Universiti Malaya (UM). Her research interests include hybrid network, wireless communication, QoS provisioning, WiMAX, and LTE network. She can be contacted at email: juwita@utem.edu.my.

Murizah Kassim is Head of Publication and Innovation at the Institute for Big Data Analytics and Artificial Intelligence (IBDAAI), Universiti Teknologi MARA, UiTM Shah Alam, Selangor, Malaysia. She is an Associate Professor from the School of Electrical Engineering, College of Engineering, UiTM. She received her PhD in electronic, electrical, and system engineering in 2016 from the Faculty of Built Environment and Engineering, Universiti Kebangsaan Malaysia (UKM). She has published many indexed papers related to computer networks, data engineering, IoT, and Web and Mobile development applications research. She has experience for 19 years in the technical team at the Centre for Integrated Information Systems, UiTM. She is also an associate member of the Enabling Internet of Things Technologies (ELIoTT) research group UiTM. She joined the academic in January 2009 and is currently a member of MBOT, IEEE, IET, IAENG, and IACSIT organizations. She can be contacted at email: murizah@uitm.edu.my.