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Impact of Parameter Adjustments in IEEE 802.15.6 MAC Protocol for Wireless Body Area Networks

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Abstract — The WBAN requires a MAC protocol that complies with the specific requirements and specifications of the body area network communication. Typically, this technology is implemented using the IEEE 802.15.6 standard, which employs the CSMA/CA mechanism. The WBAN confronts the challenge of managing the probability of heavy traffic due to the substantial medical data generated by numerous biomedical sensors. This scenario could lead to network congestion, increasing delay and packet losses, thereby posing a risk of network instability. Hence, selecting appropriate parameters is crucial for developing a MAC protocol to reduce delay and packet losses while enhancing the network throughput. This paper evaluates the performance of the IEEE 802.15.6 MAC protocol by modifying parameters such as packet rate, simulation duration, and the number of sender nodes. The IEEE 802.15.6 MAC protocol implementations are assessed regarding delay, throughput, and packet loss using the Castalia-3.3 framework based on the OMNeT++ 4.6 platform. The outcome of this study indicates that the MAC protocol for WBAN applications can be optimized by configuring the parameters correctly.

Keywords-WBAN, MAC protocol, CSMA/CA, IEEE 802.15.6 standard

I. INTRODUCTION

A notable progression in wireless communication technology, the Wireless Body Area Network (WBAN) is specifically crafted to operate within and on the human body. It is classified as a Wireless Sensor Network (WSN) with some similarities and significant differences [1]. Through continuous monitoring capabilities, WBAN has the potential to improve wearable computing applications and advance e-healthcare technologies. The WBAN consists of tiny, intelligent bio-sensors that may be worn or surgically implanted and uses well-established wireless technologies such as IEEE 802.15.6 and the Internet to connect to these critical components [2]. With its ability to manage large data traffic, the WBAN technology emphasizes minimizing delay and packet losses, especially under network congestion. Any deterioration in these elements could impact the overall network performance. In essence, medical help must be delivered quickly and efficiently in order to save lives and reduce mortality risk. Consequently, a proper Medium Access Control (MAC) protocol selection is critical for obtaining the best performance in terms of delay, network throughput, and packet losses.

Time Division Multiple Access (TDMA) and Carrier Sense Multiple Access (CSMA) are two commonly used MAC protocols in the WBAN scenario, as described in [3]. Nonetheless, the sensor devices used in WBAN are primarily based on IEEE 802.15.6 technology. This IEEE standard implements the CSMA network communication technique explained in [4]. The CSMA is a contention-based protocol that checks the shared media before transferring data to the intended destination node. It has two variants such as Carrier Sense Multiple Access with Collision Detection (CSMA/CD) and Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA). As the number of sender nodes and transmission rates increases, CSMA's capacity to maximize bandwidth and network throughput suffers significantly. This constraint stems from the possibility of the data packet and acknowledgment frame collisions within a given time range.

This paper evaluates the MAC protocol based on the IEEE 802.15.6 standard. The assessment incorporates critical parameters, including packet rate, simulation time, and the number of sender nodes, to measure performance metrics such as delay, network throughput, and packet loss. The structure includes a review of the standard, the CSMA/CA mechanism, and related work. Furthermore, it describes the MAC protocol implementation, an elucidation of methodologies, and parameter settings for simulations. Lastly, the conclusion and future work are outlined.

II. LITERATURE REVIEW

This section delves into several essential topics. First, it delves into the IEEE 802.15.6 communication standard, the foundation for WBAN technology. The CSMA/CA method, critical in managing channel access and collision avoidance within IEEE 802.15.6, is then addressed. It also examines related publications that provide context and insights into the more prominent topic of WBAN communication standards and protocols.

A. IEEE 802.15.6 Standard

In 2012, IEEE Task Group Six (TG6) published the IEEE 802.15.6 standard, which primarily established communication protocols for sensor devices operating in a WBAN [4]. The MAC layer supports three Physical (PHY) layers, as described by the standard: Narrowband (NB), Ultra-Wideband (UWB), and Human Body Communications (HBC) [5]. The IEEE 802.15.6 standard enables operational flexibility through the integration of beacon and non-beacon modes, offering three distinct configurations [6]:

(i) A superframe in beacon mode
(ii) A superframe in non-beacon mode
(iii) Without a superframe in non-beacon mode

A superframe in beacon mode is the most practical because it allows the hub to break the superframe into numerous sub-periods to provide diverse channel access periods. The superframe structure of IEEE 802.15.6 in beacon-enabled mode is depicted in Fig. 1. The superframe contains nine access phases, which are as follows [7]:

(i) The network prioritizes transmitting critical or emergency traffic during the Exclusive Access Period (EAP1 and EAP2). Sender nodes with the highest User Priority (UP) compete for channel access using the slotted ALOHA or CSMA/CA approach.
(ii) The sub-period of the Random Access Period (RAP1 and RAP2) is allocated for control traffic management. Sender nodes compete during the access phase to send the management and data frames using a prioritized ALOHA or CSMA/CA technique.
(iii) The Managed Access Period (MAP1 and MAP2) sub-period can be scheduled or unscheduled based on pre-reservation via connection request and connection assignment frames.

The hub can deactivate all access phases except RAP1, as this particular phase plays a pivotal role in establishing and disbanding sender node affiliations within the network, as outlined by the IEEE 802.15.6 standard specification.

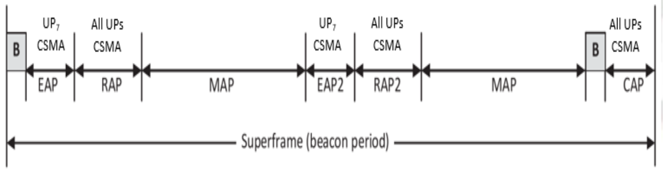


Figure 1. A superframe in Beacon Mode [4]

B. CSMA/CA Mechanism

The CSMA/CA approach is used in the IEEE 802.15.6 standard, and the flowchart in Fig. 2 simplifies the MAC mechanism for CSMA/CA within the IEEE 802.15.6 framework. When a sender node detects that the communication channel is congested, it must wait a predefined amount of time before attempting another data transmission. The node continuously examines the shared medium during this period to check if it becomes available. The distinctive factor between CSMA/CA and CSMA/CD lies in their approaches for handling a congested communication channel. To assist the acquisition of a new contended allocation, IEEE 802.15.6 employs a Back-off Counter (BC) and a Contention Window (CW) [8]. To execute the CSMA/CA method, a node with a new packet to broadcast must keep a CW open to detect a new contended allocation. This CW is in the CWmin to CWmax range, whereas BC is in the interval [1, CW]. When a node competes to transmit a packet, it sets its BC to a random integer value distributed uniformly over the range [1, CW]. This method reduces the likelihood of collisions. A node selects the CW with a transmission packet as follows:

(i) If the node has not previously acquired a contested allocation, successfully sent a data frame, or does not require an acknowledgment following frame transmission, the CW will be set to CWmin.
(ii) If an event is fails, such as the certain node not receiving acknowledgement for its most recent frame transmission, it will keep the CW at its current value if this is the mth successive failure, where m is an odd integer. The CW will be doubled otherwise.
(iii) The node will set the CW to CWmax if doubling the CW yields a number greater than CWmax

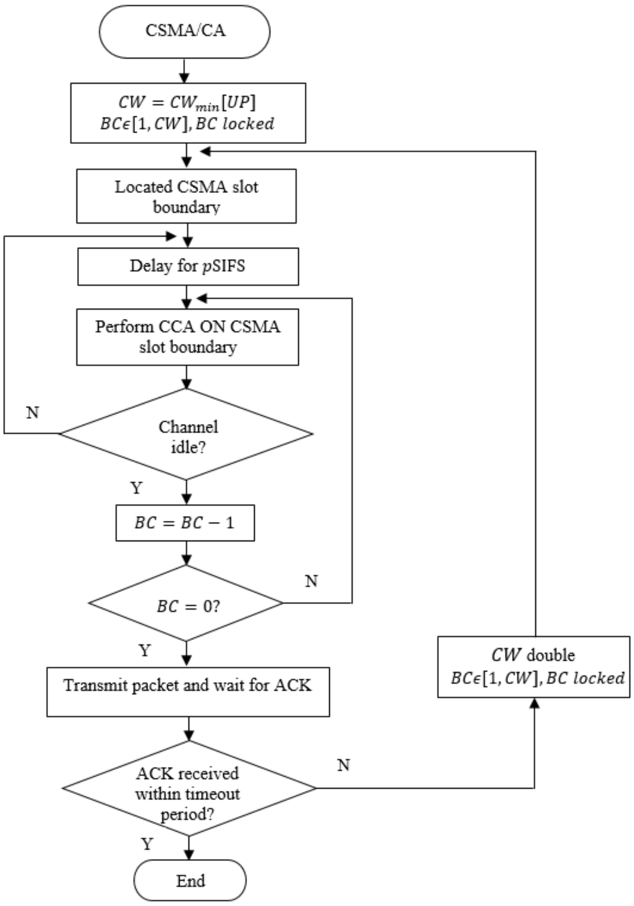


Figure 2. IEEE 802.15.6 CSMA/CA flowchart [9]

C. Related Works

Several MAC protocols are introduced in [10], namely ZigBee, BanMAC (IEEE 802.15.6), Time-out-MAC (T-MAC), Sensor-MAC (S-MAC), and Berkeley-MAC (B-MAC). These protocols are assessed for performance using the Castalia simulator, focusing on two node configurations to evaluate packet congestion, power consumption, and average delay. The simulation results indicate that the ZigBee MAC and S-MAC experience significant delays in high-traffic scenarios. T-MAC and S-MAC, on the other hand, demonstrate superior performance in terms of average power consumption. In addition, T-MAC shows better congestion avoidance capabilities across varying traffic loads.

Another study conducted in [11] investigates the impact of different body sensor data levels, with and without path loss variations, and considers access schemes like TDMA and CSMA/CA. The effectiveness of the IEEE 802.15.4 MAC protocol is assessed under two conditions: with and without a Guaranteed Time Slot (GTS). The simulation results confirm the protocol's superior performance without path-loss variations. [12], compares IEEE 802.15.4 with IEEE 802.15.6, considering throughput, energy consumption, and latency as part of the performance evaluation. Castalia-3.3 is used in [13], to simulate the performance of IEEE 802.15.4, IEEE 802.15.6, S-MAC, and T-MAC protocols, with an emphasis on latency and average energy utilization. The simulations demonstrate that hybrid networks, specifically those incorporating IEEE 802.15.4 and IEEE 802.15.6 MAC protocols, outperform scenarios with time constraints. On the other hand, S-MAC and T-MAC prove to be more efficient in situations characterized by energy constraints.

III. METHOD AND IMPLEMENTATION

This section delves into the methods and implementation of the MAC protocol, including essential features such as the structure of the MAC protocol, processes that govern state transitions, and simulation settings.

A. MAC Protocol Superframe

This study features a MAC protocol superframe consisting of a beacon and RAP1 phases, as illustrated in Fig. 3. Each superframe encompasses 32 time slots, with each slot having an allocation size of 10ms. The RAP1 periods consist of 8 time slots. The simulation runs for a duration of $t = 50s$, resulting in 156 superframes within the WBAN network.

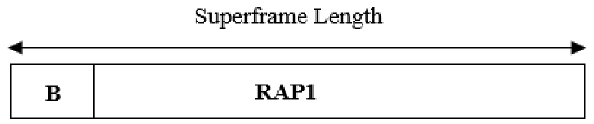


Figure 3. MAC protocol superframe structure

The hub distributes beacon frames throughout the WBAN network during the beacon phase to create synchronization among sender nodes. The sender nodes initiate the connection operation after receiving a beacon frame from the hub. After receiving connection request frames from numerous sender nodes, the hub sends an Acknowledgment (ACK) to each sender node. It sends a connection assignment frame during the RAP1 phase to confirm the node's network affiliation. All sender nodes attempt to join the network at this phase. However, some may encounter connectivity challenges for the following reasons:

(i) Certain sender nodes might encounter challenges in sending or receiving the connection request frame and connection assignment frame, particularly in scenarios involving numerous sender nodes or in the presence of significant fading or body shadowing.
(ii) In some instances, sender nodes may miss the initial beacon from the hub due to late arrivals or waking up from an inactive state. In such cases, the unconnected sender nodes remain active, awaiting the next beacon to submit connection request frame during the subsequent RAP1 period.

The hub receives request frames from sender nodes attempting to transfer data in the following superframe and determines the frame type by analyzing the frame type and frame subtype fields. Following that, the sender node competes for channel access via the CSMA/CA protocol. After receiving the data, the hub responds with an ACK frame to acknowledge the transmission. After the data transfer, the node stays dormant until the superframe finishes.

B. State Transition Diagram

The state transition diagrams for the MAC protocol are illustrated in Fig. 4. The hub starts synchronizing by sending a beacon frame to the sender nodes. The sender nodes then check the wireless channel for connection formation and, if successful, change from MAC_SETUP to MAC_ RAP1. The sender nodes then determine whether adequate slot allocations are available for data packet delivery. If there are insufficient slots, they fall back to MAC_SETUP. However, the sender nodes can complete the data packet transmission if enough slots are available. After finishing the data transmission, the sender node switches from MAC_RAP1 to MAC_SLEEP and remains dormant until the sleep period finishes.

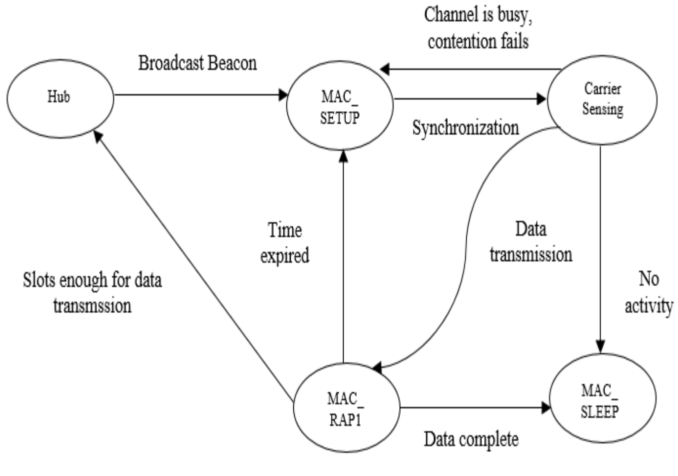


Figure 4. State transition diagram

C. Simulation Settings

Using Castalia-3.3 and OMNeT++ 4.6, the performance of the MAC protocol is analyzed by utilizing the fixed superframe structure defined by IEEE 802.15.6. This structure comprises a beacon phase and a RAP1 period, where the RAP1 period employs a contention-based technique. The slot allocation algorithm of the IEEE 802.15.6 MAC protocol is characterized by a straightforward approach, utilizing the First in, First Out (FIFO) mechanism and the specifics of the various parameter settings are listed in Table 1.

TABLE 1. PARAMETER SETTING

Parameters	Value
Simulation time	50 secs
Number of nodes	1 hub and 5 sender nodes
Contention slot size	0.36 msecs
Allocation slot size	10 msecs
Superframe length	32 slots
RAP1 length	8 slots
pSIFS	0.03 msecs

IV. RESULTS AND DISCUSSIONS

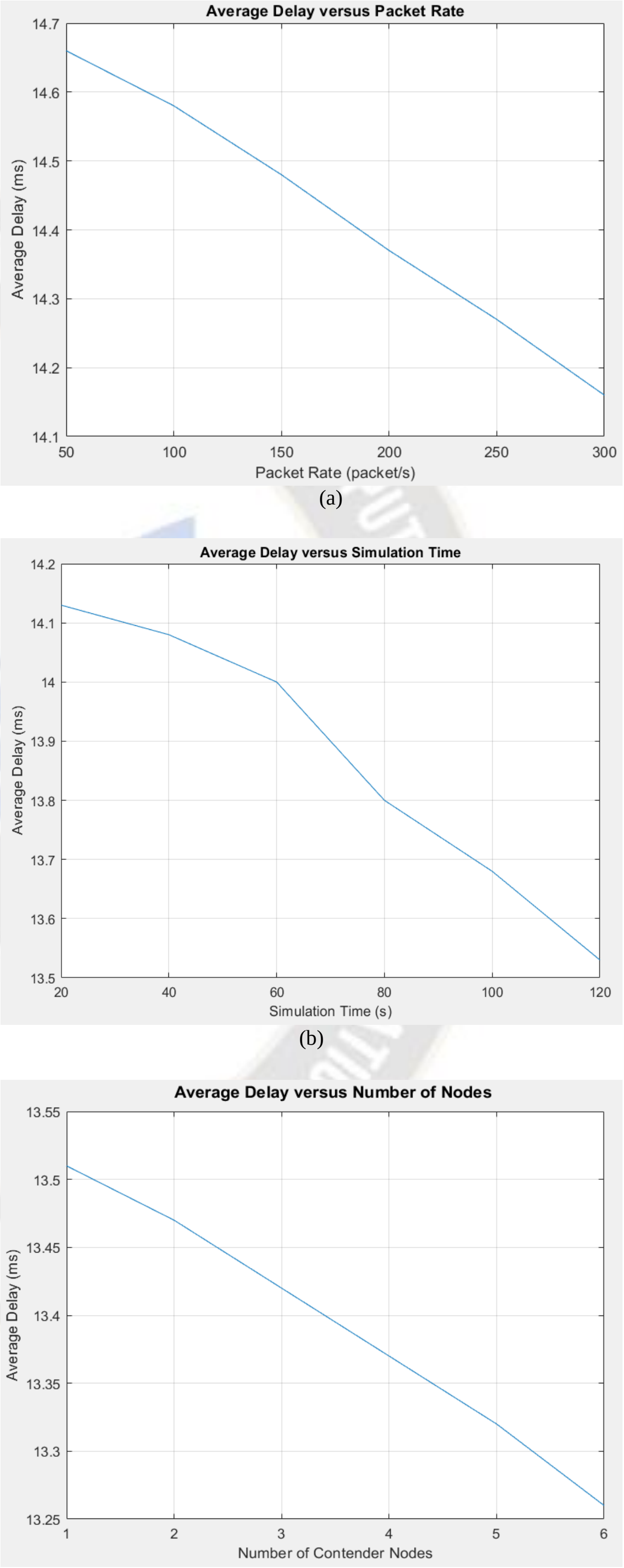
The performance of the IEEE 802.15.6 MAC protocol focusing on key metrics such as delay, network throughput, and packet loss are presented in this section.

A. Average Delay

The average delay time is defined as the duration between the generation of a packet at the sender's MAC layer and its subsequent arrival at the receiver's MAC layer [14]. Fig. 5(a) depicts the average delay performance as the packet rate varies. The higher packet rates can lead to a decrease in delay. This is because packets are transmitted more frequently, with less waiting time between transmitting consecutive packets. As a result, data can be delivered to the receiver more quickly. In summary, the packet rate significantly influences the delay performance of a network. The higher packet rates tend to reduce the delay, while lower packet rates result in increased delay.

The relationship between average delay performance and simulation time is depicted in Fig. 5(b). The graph shows that as the simulation duration increases, the delay decreases. Generally, the simulation time significantly affects the delay in network simulations. Longer duration of simulation times enables the observation of transient behavior, which refers to the initial phases or fluctuations in network performance that occur when the simulation starts or when there are changes in the network conditions. Furthermore, extending the duration of simulations enhances the probability of precisely recognizing and measuring the delay during a stable state since networks might require time to stabilize.

The average delay performance is shown in Fig. 5(c) as the number of sender nodes changes. The graph shows that the average delay decreases as the number of nodes increases. This effect can be attributed to the CSMA/CA mechanism, which helps alleviate collisions when multiple nodes attempt to transmit simultaneously. Consequently, it holds the potential to enhance data transmission efficiency within the network, thereby contributing to increase WBAN reliability.



(a)

(b)

(c)

Figure 5. (a) Delay performance vs. packet rate (sim Time=50s, n=5); (b) Delay performance vs. simulation time (Packet rate=80pps, n=5); and (c) Delay performance vs. number of nodes (Packet rate=80pps, Sim Time=50s)

B. Network Throughput

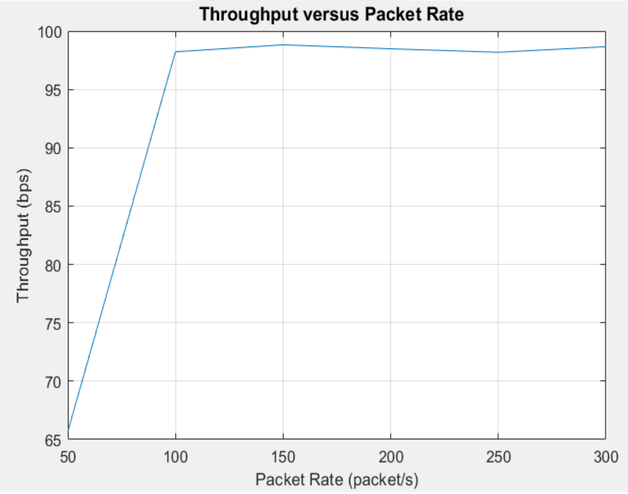
The network throughput is determined by the ratio of the total number of packets received (measured in bits) to the total simulation time (measured in seconds). The throughput can be calculated as follow:

$$Throughput = \frac{(N_{PKTRX})x(L_{PKT})}{T_S} \quad (1)$$

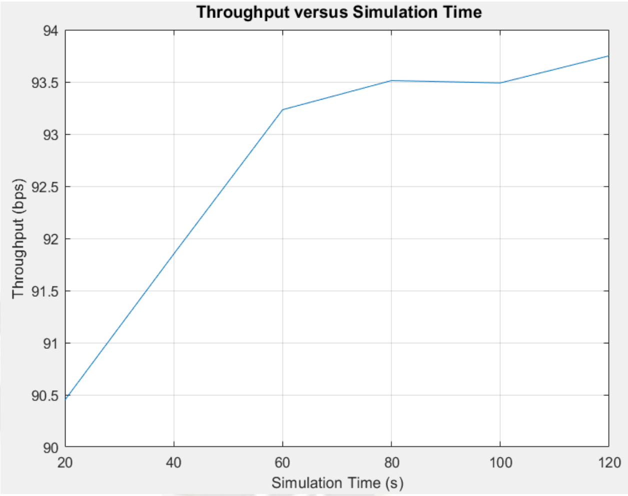
Where: N_{PKTRX} is total number of packets received by the receiver, L_{PKT} represents the size of the data packet in bits and T_S is total simulation time. Fig. 6(a) depicts the throughput and packet rate relationship. It demonstrates a linear correlation between throughput and the rate at which packets are generated and transmitted into the network. When the rate of packet generation increases, more data is introduced into the network for processing. If the network can accommodate the increased packet rate, then throughput will also likely increase.

Fig. 6(b) presents the throughput performance versus the simulation time. It is evident from the figure that as simulation time increases, throughput also increases. At the beginning of the simulation, the throughput does not immediately reach the peak performance. This initial phase frequently involves network initialization and other processes that can impact throughput, resulting in a relatively lower throughput. As the simulation progresses, the network stabilizes, and throughput gradually approaches a steady-state operation.

Fig. 6(c) provides the correlation between throughput performance and the number of sender nodes. There is a noticeable increase in throughput as the number of sender nodes increases. Throughput and the number of sender nodes exhibit a linear relationship in this case. This effect is particularly prominent when the network has sufficient capacity to handle the sender nodes without congestion. Consequently, as more nodes contend for access to the network channel, there is a higher probability that nodes can successfully transmit the data without experiencing delay, thereby leading to a corresponding improvement in throughput.



(a)



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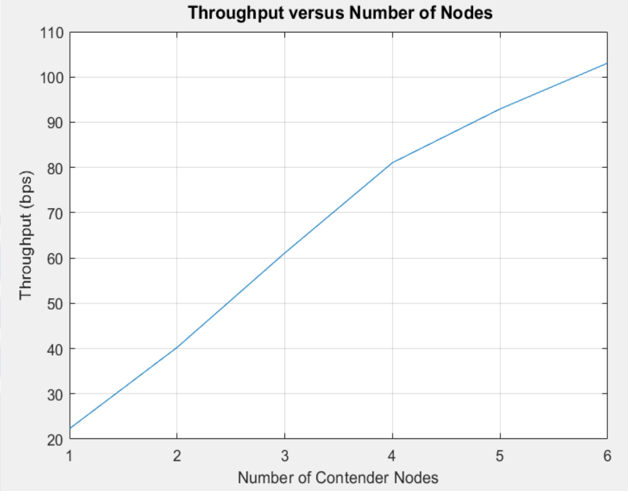


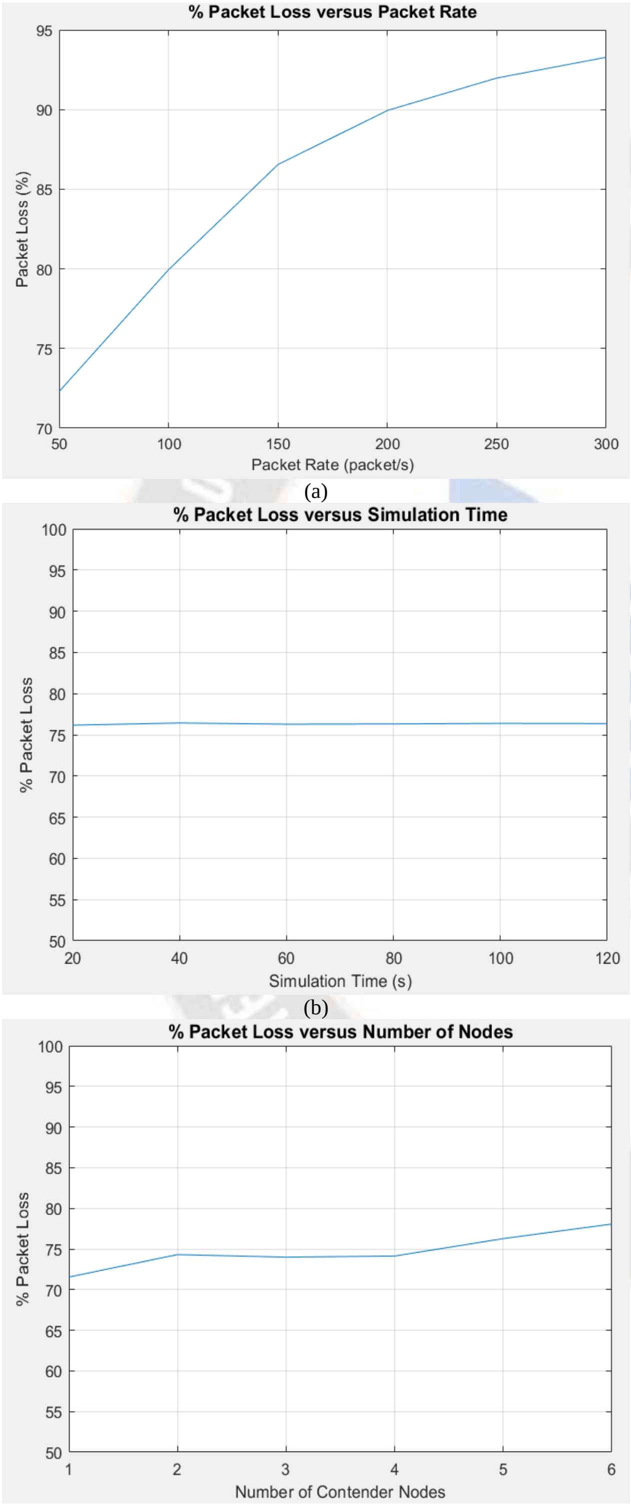
(c)

Figure 6. (a) Throughput performance vs. packet rate (sim Time=50s, n=5); (b) Throughput performance vs. simulation time (Packet rate=80pps, n=5); and (c) Throughput performance vs. number of nodes (Packet rate=80pps, Sim Time=50s)

C. Packet Loss

The packet loss signifies the quantity of packet lost while transmitting and receiving data between the source and destination [15]. Fig. 7(a) illustrates the relationship between packet loss and packet rate. The figure demonstrates that as the packet rate increases, there is a corresponding rise in the packet loss. This phenomenon occurs because higher packet rates can result in more collisions and interference. Multiple devices attempting concurrent transmissions necessitate packet retransmissions, thereby elevating the chances of packet loss.

Fig. 7(b) shows the packet loss and simulation time relationship. The figure shows that the packet loss remains consistent as the simulation time increases. This indicates that packet loss stabilizes over time as network protocols adapt to the simulated conditions. The network tends to reach a stable state where it efficiently manages traffic, resulting in consistent packet loss. Fig. 7(c) depicts the packet loss versus number of sender nodes. The figure demonstrates that the packet loss rises as the number of nodes increases. The number of sender nodes influences the contention-based access, where multiple nodes attempt to access the network simultaneously. As the contention increases due to more nodes contending for the communication channel, there is a higher probability of packet collisions and subsequent packet loss.



(a)

(b)

(c)

Figure 7. (a) Packet loss performance vs. packet rate (sim Time=50s, n=5); (b) Packet loss performance vs. number of nodes (Packet rate=80pps, Sim Time=50s); and (c) Packet loss performance vs. number of nodes (Packet rate=80pps, Sim Time=50s)

V. CONCLUSION

This paper aimed to assess the performance of the IEEE 802.15.6 MAC protocol by analyzing key parameters such as packet rate, simulation time, and sender node number. The simulation tool is OMNeT++ 4.6 with the Castalia-3.3 framework, and the study covers performance parameters such as average delay, throughput, and packet loss. The findings from the experiment indicate that modifying the parameters could optimize the MAC protocol for WBAN applications. This study can be further investigated by introducing a procedure to accommodate various types of priority for packets, including periodic, urgent, and on-demand data. This will improve the performance of the MAC protocol in diverse scenarios while prioritizing different types of data transmissions accordingly.

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