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Modeling of priority-based queuing algorithm for low-power wireless body area network

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***Abstract*—This paper presents a novel mathematical framework utilizing an M/M/1 queuing algorithm with non-preemptive priority, modeled using SimEvents in MATLAB. The proposed framework evaluates the main Quality of Services (QoS) metric, specifically average delays across high, medium, and low priority queues. Comparison between the simulated M/M/1 queuing model and its theoretical calculations demonstrated close alignment, with the simulated results closely approximating the theoretical values. This validation confirms the effectiveness of the simulation model in representing the theoretical framework. Additionally, the framework complies with the IEEE 802.15.6 standard by maintaining average delays below the 125 ms threshold across all priority levels.**

***Keywords*—mathematical framework; queuing algorithm; QoS; average delays; priority levels**

I. Introduction

In the era of advanced technology, healthcare providers are increasingly exploring the potential of digital health solutions for remote patient monitoring and treatment using Internet-connected sensors and medical devices. Wireless Body Area Network (WBAN) serves as a critical enabler of remote health monitoring by providing cost-effective and efficient real-time solutions. As depicted in Fig. 1, the WBAN communication architecture is structured into three distinct tiers, namely Tier–1 (Intra-WBAN), Tier–2 (Inter-WBAN), and Tier–3 (Beyond-WBAN). Intra-WBAN serves as the foundational component of WBAN communication and is responsible for transferring personal data to the inter-WBAN for further processing [1]. The second tier facilitates communication between intra-WBAN coordinators and other entities, such as Access Points (APs) or co-existing Body Area Network (BAN) [2]. Beyond-WBAN communication significantly enhances the application of WBAN in healthcare by enabling healthcare professionals and emergency teams to access vital patient information in real-time from any location. Defined by the IEEE 802.15.6 standard [3], WBAN comprises a set of low-power, lightweight, and miniaturized sensor nodes deployed on or implanted in the human body, enabling continuous monitoring of physiological parameters [4]-[5]. These sensor-based networks have emerged as a viable alternative to traditional wired medical systems, significantly improving the patient's quality of life [6]-[7].

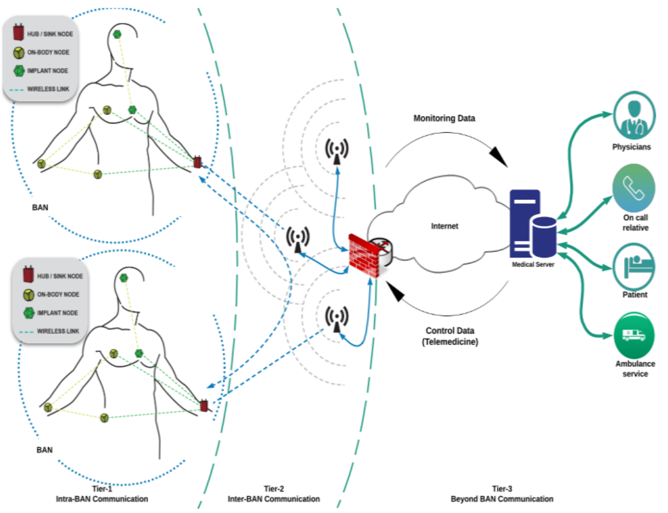

Fig. 1. Communication tiers in WBAN architecture [8]

WBAN biomedical sensors generate heterogeneous data flows with varying traffic patterns and data rates. These data are classified into three different categories, namely on-demand, emergency, and periodic traffic, each serving distinct healthcare needs. On-demand traffic is initiated by medical professionals for diagnostic or treatment purposes. It can be continuous, such as during surgeries, or discontinuous, when intermittent data exchange between a medical practitioner and patient is required. This type of traffic typically includes voice, audio, or video transmissions, which are triggered by user actions or healthcare requests. On the other hand, emergency traffic is triggered when the condition of a patient exceeds a predefined threshold, such as a critical drop in oxygen saturation. This traffic is inherently unpredictable and not generated at regular intervals. Sensors like Electrocardiogram (ECG), Electroencephalogram (EEG), Electromyography (EMG), and Oxygen Saturation (SpO_2), generate emergency traffic to monitor critical physiological parameters, requiring immediate transmission to ensure timely

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medical intervention. Periodic traffic involves routine patient monitoring at fixed intervals to track stable conditions or manage chronic diseases. It supports long-term healthcare activities, such as gastrointestinal diagnostics, neurological disorder monitoring, cancer detection, rehabilitation, and heart disease management. Blood pressure monitors, motion detectors, and skin temperature sensors generate periodic traffic for regular health monitoring under relatively stable conditions. Unlike emergency traffic, periodic traffic follows a predictable pattern. The WBAN coordinator manages the transmission of these different traffic types, ensuring efficient data flow to telemedicine or medical servers.

Efficient prioritization of WBAN traffic is critical, with higher priority allocated to emergency and critical data [9]. Data from multiple sensing devices must be transmitted simultaneously to the network coordinator while satisfying diverse Quality of Service (QoS) requirements. Failure to achieve effective prioritization can result in degraded network performance, including low priority data starvation, inefficient resource utilization, and unreliable transmission. Furthermore, the demands for QoS change significantly across different WBAN applications. For instance, non-medical applications require packet delays of less than 250 ms, whereas medical applications necessitate stricter limitations, with packet delays below 125 ms [10]. Provisioning QoS is a challenging task, and one way to improve QoS is to minimize packet loss so that reliable transmission can be achieved, which is crucial for life-saving information. Although priority queuing algorithms for WBAN have been extensively studied, existing models encounter limitations in guaranteeing QoS under varying traffic conditions. Hence, robust queuing techniques are essential for optimizing traffic management, prioritizing high priority data, and fulfilling the QoS requirements of various WBAN traffic [11]-[12].

To ensure the required QoS, we introduce a novel mathematical framework based on the M/M/1 queuing algorithm with non-preemptive priority to evaluate the main QoS metrics, namely the average delays for each priority queue. The proposed framework is implemented using SimEvents in MATLAB, which is a robust platform that enables the modeling of the M/M/1 priority queuing algorithm without requiring complex mathematical formulations. The performance is assessed by comparing the mean waiting times determined from theoretical expressions with the average delays obtained through SimEvents simulations.

II. Related Works

Several mathematical models have been proposed to evaluate WBAN performance, offering comprehensive insights that overcome the limitations of predefined simulation scenarios. For example, [11] introduced two analytical sub-models based on the IEEE 802.15.6 standard to manage heterogeneous traffic with different priorities. The first sub-model utilized the renewal rewards process to characterize the CSMA/CA back-off mechanism, while the second sub-model, an M/G/1 non-preemptive priority queuing model, aimed to reduce delays for non-emergency traffic while improving the delivery rate for high priority emergency traffic.

Additionally, in [13], the authors proposed an analytical framework for low-power BAN, categorizing sensor node traffic into critical, streaming, and non-critical types. To address WBAN QoS requirements, they utilized a G/M/1 queuing model with three priority-based queues. Building on this work, [14] extended the analysis of a G/M/1 queuing model with multiple traffic classes generated from various WBAN events, distinguishing between event-driven and application-driven traffic. In [15], a prioritized queuing mechanism was developed for the IEEE 802.15.6 standard, incorporating three priority queues at the Medium Access Control (MAC) layer to minimize delays and enhance reliability.

In [16], an analytical model for IEEE 802.15.6 CSMA/CA mechanism was proposed for a non-saturated, error-prone channel with finite load. It integrates a DTMC-based Markov chain, back-off duration, and Geo/G/1 queuing sub-models, enabling computation of access probabilities and idle periods while addressing user priorities. Likewise, [11] developed two analytical sub-models for heterogeneous traffic in IEEE 802.15.6. The first uses a renewal rewards process for the CSMA/CA back-off, while the second employs an M/G/1 queuing model with non-preemptive priority to manage emergency traffic, reducing non-emergency delays and enhancing emergency traffic delivery.

Further studies analyzed queuing techniques for IEEE 802.15.6-based WBAN. For instance, [17] demonstrated that Priority Queuing (PQ) and Low Latency Queuing (LLQ) significantly improved delays and delivery rates. A QoS-driven approach was introduced in [18] to address challenges such as energy consumption, time-varying channels, and contextual variations in WBAN. This work employed an M/D/1 queuing model to evaluate delays performance and developed an on-body channel model using a two-state Markov process, classifying nodes into "good" and "bad" states. The model categorized traffic into one normal and four abnormal contexts to meet QoS requirements. Additionally, the authors in [19] employed a D/G/1 queuing model for normal traffic transmission and an M/G/1 queuing model for emergency traffic transmission. Both models focused on minimizing system energy consumption while meeting QoS requirements under dynamic link conditions influenced by postural changes.

To the best of our knowledge, no prior studies have utilized SimEvents as a mathematical framework for evaluating WBAN performance. To address this gap, we utilize SimEvents in MATLAB to model a non-preemptive M/M/1 priority-based queuing algorithm for analyzing key QoS metrics, specifically average delays across various medical traffic classes in WBAN. The proposed model prioritizes data using three distinct queues such as high priority for emergency traffic, medium priority for periodic traffic, and low priority for non-critical traffic. High priority queues are served first, ensuring minimal delays for critical data and enhancing the reliability and effectiveness of WBANs in e-health applications.

III. Non-Preemptive M/M/1 Priority Queuing Model

A. Mathematical Model

We propose a non-preemptive M/M/1 queuing model to prioritize high priority traffic over medium and low priority traffic without interrupting ongoing transmissions, as described in [20]. The model assumes a Poisson arrival process and exponential service times for each priority level. Let μ_k represent the mean service rate for priority k. The mean waiting times, W_k for traffic of priority $k = 1, 2,$ and 3 is expressed in Equation (1):

$$W_k = \frac{A_k}{B_{k-1}B_k} + \frac{1}{\mu_k} \quad (1)$$

where, A_k and B_k are defined as:

$$A_k = \sum_{i=1}^{k} \frac{\lambda_i}{\mu_i^2} \quad (2)$$

$$B_k = 1 - \sum_{i=1}^{k} \frac{\lambda_i}{\mu_i}, \text{ and } B_0 = 0 \quad (3)$$

Hence, the expected waiting times for Queue-1 (Q_1), Queue-2 (Q_2), and Queue-3 (Q_3) are as follows:

For $k = 1$,

$$W_1 = \frac{A_1}{B_{1-1}B_1} + \frac{1}{\mu_1}, A_1 = \sum_{i=1}^{1} \frac{\lambda_i}{\mu_i^2}, B_1 = 1 - \sum_{i=1}^{1} \frac{\lambda_i}{\mu_i}$$

For $k = 2$,

$$W_2 = \frac{A_2}{B_{2-1}B_2} + \frac{1}{\mu_2}, A_2 = \sum_{i=1}^{2} \frac{\lambda_i}{\mu_i^2}, B_2 = 1 - \sum_{i=1}^{2} \frac{\lambda_i}{\mu_i}$$

For $k = 3$,

$$W_3 = \frac{A_3}{B_{3-1}B_3} + \frac{1}{\mu_1}, A_3 = \sum_{i=1}^{3} \frac{\lambda_i}{\mu_i^2}, B_3 = 1 - \sum_{i=1}^{3} \frac{\lambda_i}{\mu_i}$$

Here, Q_1 represents the highest priority queue, Q_2 corresponds to medium priority queue, and Q_3 denotes the lowest priority queue. The parameter λ_i represents the arrival rate for priority i, while μ_i denotes the corresponding service rate. These equations characterize the behavior of the queuing model across different priority levels, thereby ensuring efficient traffic management and prioritization in WBAN environments.

B. SimEvents Modeling and Implementation

This part presents a non-preemptive M/M/1 priority-based queuing algorithm to evaluate the average delays for different traffic classes in WBAN. The proposed queuing algorithm is implemented using SimEvents in MATLAB, providing a mathematical framework for WBAN performance analysis. SimEvents is a specialized simulation tool for constructing and analyzing discrete-event system models. SimEvents toolbox in MATLAB provides an environment for modeling and simulating discrete-event system models. It offers a comprehensive library of pre-built blocks, including queues, servers, and gates, which can be interconnected in block diagrams similar to Simulink models. Additionally, this toolbox facilitates the collection and analysis of performance metrics such as delays, resource utilization, and throughput, which are essential for network operation optimization and performance evaluation.

The proposed model prioritizes high priority queue over lower priority ones by following a non-preemptive priority rule, where ongoing transmissions are not interrupted. This approach is well-suited to WBAN scenarios, where abrupt interruptions could disrupt data integrity and degrade network performance. The architectural framework of the proposed queuing model is depicted in Fig. 2. It considers three different types of traffic arriving at the sensor node, categorized into k packet queues, Q_k, where $k = 1, 2,$ and 3, with Q_1 representing the highest priority queue. This prioritization scheme is designed to accommodate the unique characteristics of WBAN traffic.

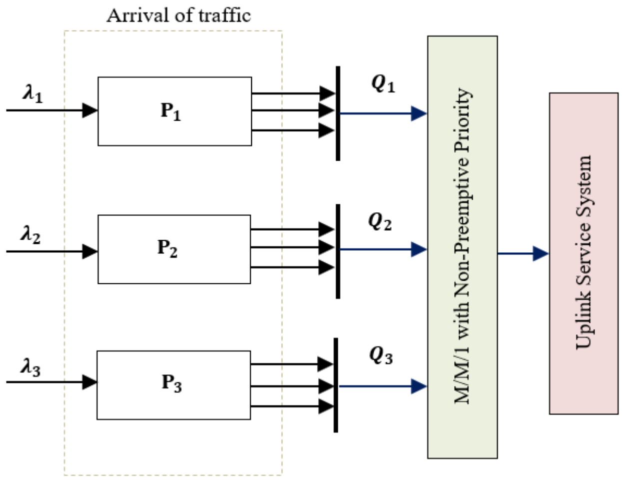

Fig. 2. Proposed queuing model framework

Traffic arrivals at sensor nodes are modeled using Poisson distribution, simplifying queue performance analysis. The Poisson traffic arrival rate of queue-k at time t is denoted as $\lambda_k(t)$. The inter-arrival time of a Poisson traffic arrival process is an exponential random variable represented in Equation (4):

$$\lambda_k(t) = \frac{1}{(Mean\ Inter-arrival)} \quad (4)$$

In the proposed scheme, sensor nodes enter a sleep state after completing scheduled transmission slots while other nodes are scheduled for transmission. This sleep state is viewed as the server's vacation from a queuing perspective. Each queue takes T_{slot} to complete one frame transmission and is specified in Equation (5):

$$T_{slot} = T_x = T_{data} + T_{ACK} + T_{SIFS} \quad (5)$$

Thus, the service rate, $\mu_k(t)$ of the queue-k at the time t is given by Equation (6):

$$\mu_k(t) = \frac{1}{T_{slot}} \quad (6)$$

Where, the service time is defined as the total time to transmit a packet, T_{slot} including the time to transmit a data packet, T_{data}, SIFS duration, T_{SIFS} and the time of the acknowledgment packet, T_{ACK}. The utilization factor, $\rho_k(t)$ is represented in Equation (7):

$$\rho_k(t) = \frac{\lambda_k(t)}{\mu_k(t)} = T_{slot}\lambda_k(t) \quad (7)$$

Packet drops due to buffer overflow are not considered in this model. Therefore, for the stability of the proposed queuing system, the total traffic load must satisfy the following condition, as represented by Equation (8):

$$\rho_1(t) + \rho_2(t) + \rho_3(t) < 1 \quad (8)$$

Table I outlines the mapping of various traffic classes to queue prioritization. Packet arrivals at each queue follow independent Poisson processes with rates λ_1, λ_2, and λ_3. Additionally, the corresponding block diagram in Fig. 3 shows the integration of a Simulink function for the entity generator with an arrival rate value determined from Table I. In this configuration, an arrival rate of 20 is applied, which the function *exponentialArrivalTime1* uses to compute the inter-arrival times. Fig. 4 further details the implementation of the exponential distribution, showing how the arrival rate is used with a uniform random number generator to accurately model the time between arrivals. The implementation of the queuing model in SimEvents is depicted in Fig. 5.

TABLE I
MAPPING OF WBAN TRAFFIC TO QUEUE PRIORITIZATION

Priority Queue	Priority Level	Traffic Types	Arrival Rate (p/s), λ_k
Q_1	High (P_1)	Emergency	20
Q_2	Medium (P_2)	Periodic	10
Q_3	Low (P_3)	Non-critical	5

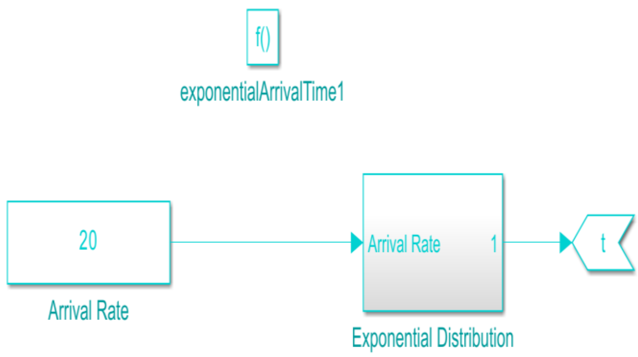

Fig. 3. Simulink function block

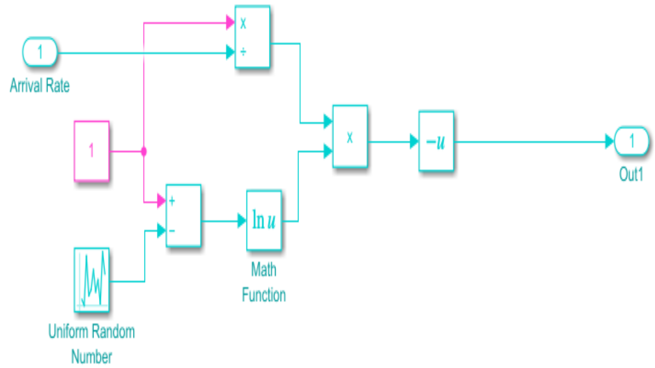

Fig. 4. Exponential distribution block

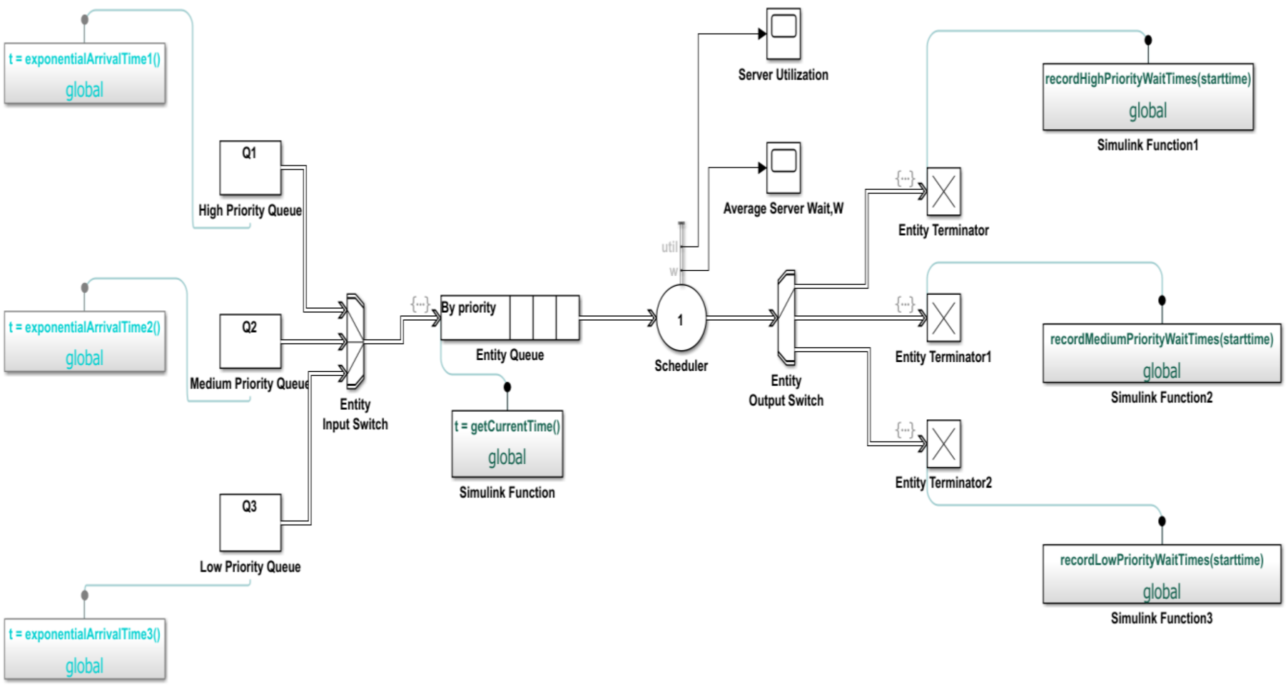

Fig. 5. Proposed queuing model in SimEvents simulator

IV. Results and Discussion

The performance evaluation involves solving the theoretical expressions and implementing the simulation model using SimEvents in MATLAB. The results are analyzed by comparing the mean waiting times derived from the theoretical expressions with the average delays obtained from the SimEvents simulation.

Fig. 6 illustrates the mean waiting times for the priority queuing model across three queues with distinct priority levels. $\boldsymbol{Q_1}$, denoting the highest priority queue, exhibits the shortest mean waiting times of 20.74 ms, indicating that high priority traffic experiences minimal delays. $\boldsymbol{Q_2}$, designated as medium priority queue, demonstrates an increased mean waiting times of 42.57 ms, reflecting its intermediate priority level. Meanwhile, $\boldsymbol{Q_3}$, representing the lowest priority queue, has the longest mean waiting times of 79.84 ms, highlighting the reduced priority assigned to this traffic class. These findings align with the principles of the non-preemptive priority queuing model, wherein the higher priority queue is serviced first to guarantee timely data transmission, particularly for critical applications like emergency medical data. The gradual increase in mean waiting times validate that the model can effectively manage traffic prioritization, balancing the needs of high, medium, and low priority data in WBAN.

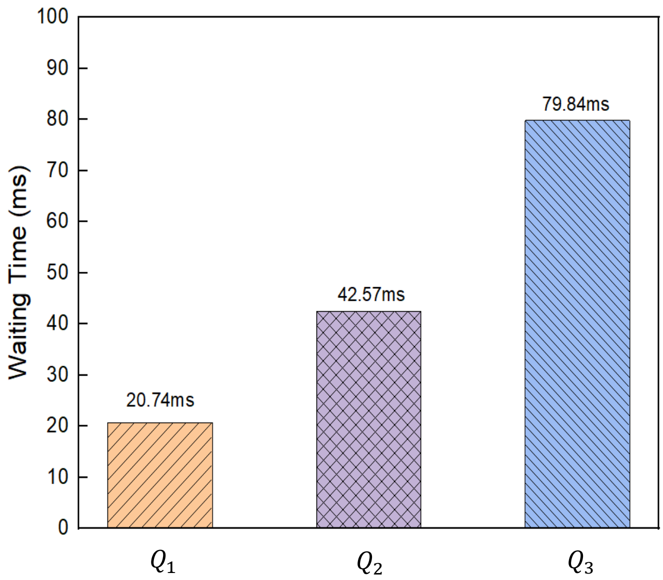

Fig. 6. Mean waiting times

Fig. 7 depicts the average delays for different priority queues. The high priority queue, $\boldsymbol{Q_1}$ consistently achieves the lowest average delays of 22.91 ms, followed by medium priority queue, $\boldsymbol{Q_2}$ at 45.17 ms, and low priority queue $\boldsymbol{Q_3}$ at 82.81 ms. The results demonstrate that $\boldsymbol{Q_1}$ exhibits the lowest average delays throughout the simulation, followed by $\boldsymbol{Q_2}$ and $\boldsymbol{Q_3}$. This performance verifies that $\boldsymbol{Q_1}$ represents the high priority queue, where these packets are prioritized and transmitted first, followed by medium and low priority queue. As a result, these packets encounter reduce delays within the network, ensuring the prompt transmission of emergency and time-critical medical data. Prioritizing high priority queue is crucial in situations where rapid data transmission can significantly influence patient outcomes, as delays in conveying critical medical information may lead to serious health risks.

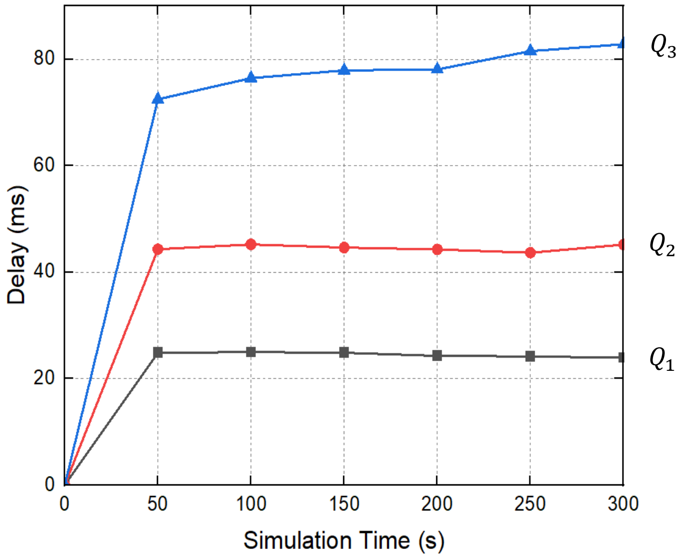

Fig. 7. Average delays

The performance results are summarized in Table II. The difference between these results is as expected, which is the calculation from theoretical equations provides a more accurate reading benchmark. Notwithstanding, when implemented in simulations, it is affected by several factors that make it slightly different from the actual results. Among the factors influencing this difference is that the simulation is performed by a system based on a discrete-event simulator. In addition, the simulations must be performed several times to obtain results that are close to theoretical, and the average value for each simulation must be considered to obtain the required readings.

Table II
Performance Comparison

Priority Queue	Priority Level	Mean Waiting Times (ms)	Average Delays (ms)
Q_1	High (P_1)	20.74	22.91
Q_2	Medium (P_2)	42.57	45.17
Q_3	Low (P_3)	79.84	82.81

V. Conclusion

In conclusion, the objective of comparing the M/M/1 queuing model simulated using SimEvents in MATLAB with its theoretical calculations was successfully achieved. Although the simulated results are not identical to the theoretical values, they closely approximated the theoretical calculations, which are considered more accurate. This alignment validates the effectiveness of the simulation model in reflecting the theoretical framework. Furthermore, the proposed framework effectively meets the IEEE 802.15.6 standard by maintaining average delays below the 125 ms threshold across all priority levels, ensuring service differentiation based on traffic priority. Future work will focus on comparing the performance of the proposed algorithm with other queuing techniques to enhance its applicability and efficiency.

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