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Frame Aggregation with Simple Block Acknowledgement Mechanism to Provide Strict Quality of Service Guarantee to Emergency Traffic in Wireless Networks

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Abstract: This paper proposes a frame aggregation with a simple block acknowledgement (FASBA) mechanism to provide a strict QoS guarantee to life-saving emergency traffic in wireless local area networks. This work builds on our previous work on a multi-preemptive enhanced distributed channel access protocol called MP-EDCA. The main difference between FASBA and MP-EDCA is that MP-EDCA does not provide a strict QoS guarantee to life-saving emergency traffic (e.g., ambulance calls), especially in high-load conditions. Our proposed FASBA protocol solves the problems of achieving a strict QoS guarantee to life-saving emergency traffic. The strict QoS guarantee is achieved by aggregating multiple frames with a two-bit block acknowledgement for transmissions. FASBA assures guaranteed network services by reducing MAC overheads; consequently, it offers higher throughput, lower packet delays, and accommodates a larger number of life-saving emergency nodes during emergencies. The performance of the proposed FASBA is validated by Riverbed Modeler and MATLAB 2024a-based simulation. Results obtained show that the proposed FASBA offers about 30% lower delays, 17% higher throughput, and 60% lower retransmission attempts than MP-EDCA under high-traffic loads.

Keywords: frame aggregation; block acknowledgment; QoS; MP-EDCA; 802.11e MAC

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1. Introduction

There has been tremendous growth in the deployment of 802.11-based wireless local area networks (WLANs), especially for use in distributed emergency applications (e.g., disaster recovery) [1–4]. These emergency applications require a strict quality of service (QoS) guarantee with the provision of in-channel preemption (i.e., channel access priority on arrival) for their high-priority emergency traffic.

The original IEEE 802.11 standard [5] does not prioritise real-time traffic and uses a Stop-and-Wait ARQ mechanism, causing significant overhead from channel sensing and immediate ACK transmissions. To address these issues, IEEE 802.11e was introduced to improve QoS for real-time applications like voice and video by defining four access categories (ACs) for differentiated channel access. However, conventional EDCA only offers relative differentiation, lacking support for emergency traffic and failing to guarantee QoS under heavy loads [6,7]. Additionally, IEEE 802.11e introduced TXOP with BlockAck schemes, which enhance throughput [8] but can lead to resequencing delays at the receiver [9].

To overcome the limitations of EDCA (providing in-channel preemption and assuring strict QoS guarantee), we previously proposed a multi-preemptive EDCA (MP-EDCA) in WLANs [10]. The proposed scheme supports emergency traffic and provides in-channel preemption. However, MP-EDCA does not offer a QoS guarantee for life-saving emergency traffic in WLANs. To address the performance issues of MP-EDCA, in this paper, we propose a frame aggregation with a simple block acknowledgement (FASBA) mechanism [10]. The proposed FASBA provides assurance of service delivery, enhances network throughput, reduces MAC transmission overhead, and ultimately accommodates several life-saving emergency nodes in high loads. Better system performance is achieved by aggregating the frames with a simple two-bit block acknowledgement. We implemented both MP-EDCA [10] and FASBA schemes in the Riverbed Modeler simulator for performance evaluation and comparison purposes. We contributed code (written in C++) by modifying Riverbed simulation process models to create new emergency communication nodes required for system simulation.

The main contributions of this study are summarised as follows:

- We propose a frame aggregation with a simple block acknowledgement (FASBA) protocol to provide a strict QoS guarantee to life-saving emergency traffic in high-load WLANs. To this end, we develop an analytical model using the Markov chain considering saturated load, retry limits, and channel conditions. We derive throughput and mean packet delays mathematically to estimate the system performance.
- We develop a simulation model using Riverbed Modeler and MATLAB simulator to validate system performance.
- We implement new life-saving emergency nodes (in C++) and the corresponding process models in the Riverbed Modeler simulation environment to study the performance of FASBA and to compare it with the existing MP-EDCA.This is a significant piece of work contributing towards the implementation of emergency traffic in WLANs. The system performance is also validated by MATLAB2024a-based simulation.

The rest of this paper is organised as follows. The related work is presented in Section 2. The proposed FASBA approach is described in Section 3. Section 4 presents an analytical model for FASBA. The system performance is evaluated in Section 5. The results are discussed in Section 6. Finally, the paper is concluded in Section 7.

2. Related Work

Emergency communication is essential to support victims and first responders in critical disaster scenarios where human lives are on the line. Wireless communication, such as cellular, WiFi, vehicle-to-infrastructure, and mesh networks based on IEEE 802.11 standards [5], are crucial in prioritising emergency communication. These standards ensure that emergency messages are delivered promptly and reliably, enabling first responders to communicate immediately with those requiring assistance. In disaster situations demanding strict quality of service (QoS), IEEE 802.11e provides low-latency communication by prioritising essential traffic through Enhanced Distributed Channel Access (EDCA), which is particularly valuable in crowded emergency environments [11]. When network infrastructure is compromised, IEEE 802.11s offers self-healing mesh networking capabilities, allowing devices to relay critical information across multiple nodes, even if some connections fail [12]. For medical emergencies, Time-Sensitive Networking (TSN) adaptations within IEEE 802.11 facilitate real-time data transmission with minimal latency and jitter, supporting rapid coordination in life-saving interventions [13,14].

IEEE 802.11p, designed explicitly for vehicular communication, supports essential vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) links, helping to prioritise messages like hazard alerts and aiding in effective evacuation and emergency vehicle routing [15,16]. When low-power, long-range communication is required, IEEE 802.11ah (WiFi HaLow) extends network reach for IoT-based emergency monitoring, ensuring connectivity with sensors that detect hazardous conditions. This is achieved through protocols like the Registration-based Situation-Aware Access Extension (RSAE), which minimises signal collisions and ensures rapid data delivery from critical sensors in densely populated disaster zones [17,18]. Additionally, IEEE 802.11ax (WiFi 6) leverages Orthogonal Frequency Division Multiple Access (OFDMA) and Target Wake Time (TWT) to reduce congestion, effectively managing high-priority traffic in areas dense with emergency responders and equipment [19]. IEEE 802.11 standards collectively establish a robust, life-saving communication framework crucial for prioritising emergency traffic and ensuring uninterrupted transmission of essential data in any disaster response.

Many network researchers have developed various techniques to enhance the performance of 802.11e by reducing overheads. Examples of techniques include modified TXOP, block size, and BlockAck. The main problem with small frame sizes is the increased transmission overheads because an STA needs to negotiate each time before transmitting the frame. To overcome the network performance issue due to the small block size, one can form a large frame by combining several short packets in a flow. However, the larger block size increases the error rate and results in a delay for real-time applications [20,21]. Thus, Sarkar and Sowerby [22] proposed a new MAC protocol called buffer unit multiple access (BUMA). The proposed BUMA protocol reduces transmission overheads by applying the frame aggregation approach and achieves higher throughput. However, BUMA is only suitable for UDP applications and may not provide a guarantee of service delivery. Similarly, Saif et al. [23] developed a MAC scheme called minimised header MAC service data unit (MSDU) aggregation scheme (mA-MSDU) for reducing the transmission overheads by aggregating MSDUs. This scheme optimised the subframe by minimising the header overhead. Furthermore, the researchers in [23] proposed an Implicit Sequence Control (ISC) as a subframe error controller that retransmits only the corrupted subframes. On the other hand, a two-level frame aggregation mechanism is suggested by combining A-MSDU and aggregate-MAC protocol data unit (A-MPDU) schemes [24]. This scheme enhanced the performance of throughput and offered a reduced MAC delay. Both A-MSDU and A-MPDU are defined by IEEE 802.11n [25] standard for achieving higher throughput at the MAC layer. Although the new frames are smaller than legacy 802.11, they did not improve the network throughput, especially when added with the small payload. Moreover, network performance is highly affected while transmitting the A-MSDUs due to a lack of control and retransmission. Implementing IEEE 802.11n does not aggregate MPDU for voice traffic due to its specific end-to-end delay requirements. Seytnazarov and Kim [26] identified that the network's performance is highly degraded in saturated traffic conditions when multiple nodes access the medium for transmitting voice traffic. The authors proposed a QoS-aware adaptive A-MPDU aggregation scheme (QAA-MPDU). The QAA-MPDU scheme optimises throughput performance by aggregating MPDU for voice traffic and reducing protocol overhead. Liu et al. [27] developed an adaptive A-MPDU MAC scheme.

Hazra and De [28] developed a frame concatenation with block acknowledgement for providing a QoS guarantee for time-sensitive applications. However, the proposed scheme is only suitable for client-server applications. To provide fairness and enhance the performance of EDCA, Kim and Cho [29] proposed an Adaptive TXOP Allocation (ATA) scheme. In the ATA scheme, stations adjust the TXOP interval based on traffic load and delay bound required by the application. The TXOP interval is increased in two steps: at first, STA increases its TXOP to satisfy the QoS guarantee required by its packet queue and then when the traffic load is low.

For reliable communication, the receiving station acknowledges every received packet. However, this mechanism decreased the overall network performance due to an increasing number of acknowledgement packets. As the solution, researchers proposed various approaches utilising and optimising block acknowledgement (Cabral et al. [30]). The optimized block acknowledgement (O-BlockAck) developed by Cabral et al. [30] reduces the delay and increases the number of users within the network. The o-BlockAck scheme uses a single service and a mixture of services used on the node. The empirical results have shown that fragment size 12 is more appropriate for a mixture of services, and supported users may be increased from 30 to 35 within a network. Another mechanism for improving the EDCA scheme is called holding time aggregation (HTA), developed by Azevêdo Filho et al. [31]. In HTA, each STA calculates the time a packet takes for its journey and the time an application may tolerate delay. However, the proposed HTA scheme is only suitable for UDP applications.

A review of the literature on frame aggregation and block acknowledgement schemes in providing better QoS and reducing transmission overhead is summarised in Table 1.

Table 1. Summary of related work on frame aggregation and block acknowledgement in WLANs.

Schemes	**Adaptive?**	**Frame Aggregation and Block Ack?**	**Strict QoS to Emergency Traffic?**	**Scalable?**	**High-Traffic Loads?**
BUMA [22]	yes	no	no	yes	yes
O-BlockACK [30]	yes	yes	no	no	yes
Adaptive A-MPDU [27]	yes	yes	no	no	yes
TXOP-based frame concatenation and BlockAck (TFCB) [28]	no	yes	no	no	yes
mA-MSDU [23]	yes	yes	no	no	no
HTA [31]	yes	yes	no	yes	no
ATA for EDCA [20]	yes	no	no	no	yes
Two-level aggregation [24]	no	yes	no	no	no
QAA-MPDU [26]	yes	no	yes	no	yes
IEEE 802.11e block ACK [21]	no	yes	no	no	yes
MU-MIMO adaptive algorithm [32]	yes	yes	no	no	no
CA-TXOP scheme [33]	no	no	yes	yes	yes
FAFA scheme [34]	yes	yes	no	yes	no
A-MPDU aggregation scheme [35]	yes	yes	no	no	yes
	yes	yes	yes	yes	yes
Our work (FASBA)	FASBA is a dynamic algorithm that provides a strict QoS guarantee for life-saving emergency traffic in high-load networks. FASBA is scalable and accommodates much emergency traffic.				

3. Proposed Frame Aggregation with Block Acknowledgment Mechanism

3.1. Revisiting MP-EDCA

The proposed FASBA scheme enhances the capabilities of our previously reported MP-EDCA [10]. The main objective of MP-EDCA is to support emergency traffic in wireless networks. This section briefly describes the MP-EDCA protocol.

3.1.1. The MP-EDCA Approach

The MP-EDCA framework implements a hierarchical quality of service (QoS) mechanism tailored for emergency communication in wireless networks. It categorises traffic into four prioritised emergency classes (Classes 1–4) and a non-priority queue for routine data (e.g., email). Class 1, designated for life-critical scenarios (e.g., life-saving interventions), holds the highest priority, followed by Class 2 (health emergencies), Class 3 (property threats), and Class 4 (environmental risks) [36,37]. This hierarchy aligns with real-world operational protocols for emergency scenarios.

The MP-EDCA employs a preemption mechanism to enforce prioritisation, allowing higher-priority traffic to seize channel access from lower-priority traffic. The protocol dynamically adjusts SIFS and slot time parameters within emergency frames, optimising contention windows and backoff intervals to minimise latency for critical services. For instance, Class 1 traffic utilises the shortest SIFS intervals to expedite medium access, while lower classes incrementally scale these timers to balance fairness and urgency. This architecture ensures deterministic performance for mission-critical applications, reflecting the ethical prioritisation of human life, health, and environmental stewardship in networked emergency response systems.

3.1.2. Limitations of MP-EDCA

A critical limitation of the MP-EDCA protocol is its inability to enforce deterministic latency guarantees for life-critical emergency traffic under high network loads. Specifically, MP-EDCA relies on probabilistic contention window adjustments and traffic prioritisation, which fail to ensure bounded packet delays when the density of emergency nodes exceeds 40. In such scenarios, network performance degrades sharply, suffering higher collision rates and unstable channel access, and cannot meet the latency thresholds required for mission-critical applications (e.g., emergency medical services or disaster response systems). The proposed FASBA mechanism introduces a hybrid MAC layer framework that combines dynamic time slot reservation with adaptive contention parameters to address this. FASBA enforces strict priority preemption for emergency traffic and optimises resource allocation in ultra-dense deployments, thereby achieving compliance with industrial QoS standards for life-saving applications.

3.2. The FASBA Approach

The main objective of the proposed FASBA is to accommodate a large number of life-saving emergency nodes in emergency times when a larger number of nodes report an emergency for channel access. It is useful to design a network protocol that can offer lower packet delays and higher throughput by reducing transmission overheads. Second, the protocol should provide a strict QoS guarantee in message delivery. To meet the objectives mentioned above, FASBA aggregates three frames with a simple BlockAck mechanism for transmissions. The FASBA adopts the idea of frame-aggregation (for reducing protocol's transmission overheads) from BUMA protocol [8]. Moreover, FASBA employs a simple two-bit BlockAck strategy for accommodating more nodes in the network and to provide a strict QoS guaranteed message delivery. This is achieved in the following ways.

In FASBA, each node (station) maintains a buffer (temporary memory) to combine and hold three packets with a single packet header and a trailer at the MAC layer before transmissions. This allows FASBA to reduce transmission overheads significantly and consequently improve system performance. Figure 1 illustrates the FASBA's frame aggregation mechanism. The figure also shows the acknowledgement mechanism followed by SIFS.

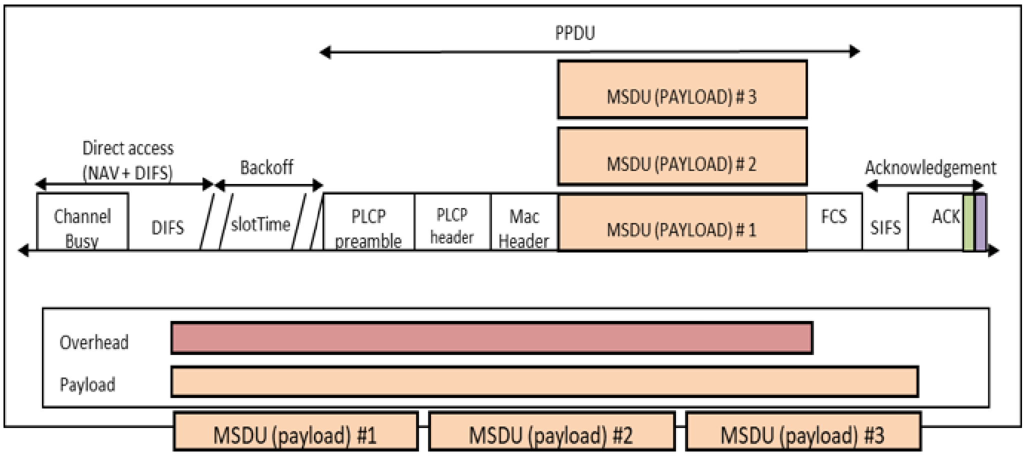


Figure 1. Illustrating frame aggregation (three packets) and two-bit acknowledgement of FASBA.

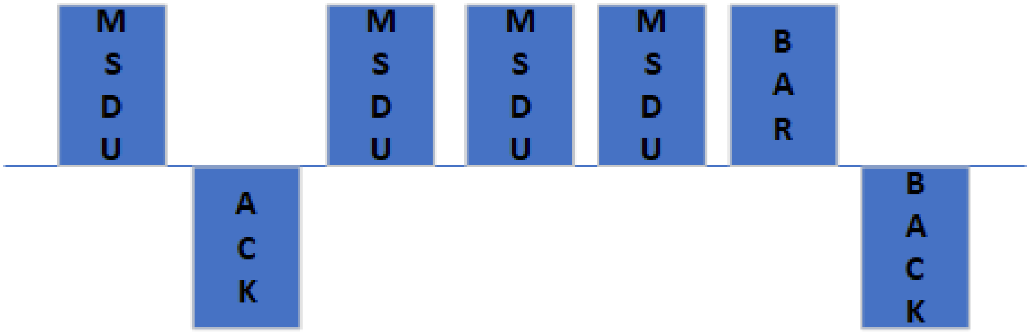
FASBA's simple block acknowledgement mechanism is illustrated in Table 2. The first column shows the two bits of acknowledgement, followed by purpose, and the next possible bits, which will be sent by the STA. If both ACK bits are 11, it means all three packets (i.e., packet 1, packet 2, and packet 3) are successfully delivered. The transmitting STA will send the subsequent three packets (i.e., packet 4, packet 5, and packet 6). If ACK bits are 01, it means packet 2 and packet 3 are transmitted successfully. The transmitting STA will send packets 1, 4, and 5. Similarly, if ACK bits are 10, it means packets 1 and packet 2 are delivered successfully, and STA will send packets 3, 4, and 5. In all other cases, all three packets will be resent. Though FASBA is designed to support emergency traffic through a modified channel contention mechanism, non-priority traffic can use a standard IEEE 802.11e multi-user contention mechanism to contend for the channel.

Table 2. FASBA's simple 2-bit BlockAck algorithm.

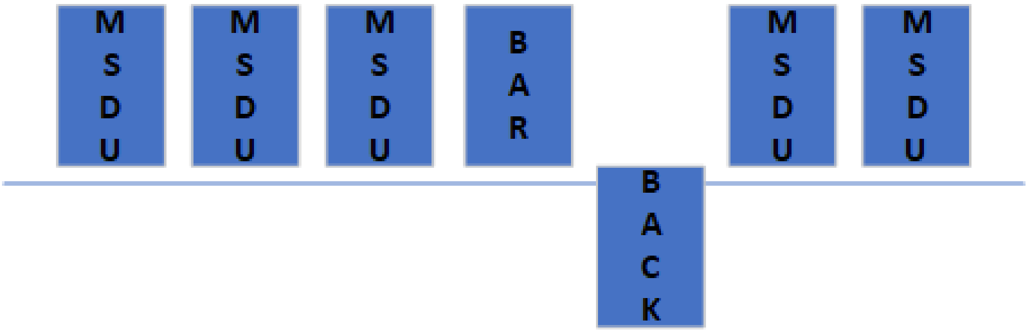
Two Bits	Purpose	Next Packets
11	All frame/packet received successfully. Transmit another one	4, 5, and 6
01	Only resend packet 1, (packet #2 and #3 received successfully)	1, 4, and 5
10	Only resend packet 3, (packet #1 and #2 received successfully)	3, 4, and 5
00/None	Resend (all three packets)	1, 2, and 3

4. Analytical Model for FASBA

The main focus of the FASBA protocol is to support guaranteed QoS for life-saving emergency nodes during emergency situations. In this work, we considered frame aggregation with a protected Block ACK mechanism. In protected Block ACK (shown in Figure 2a), the sender will transmit a single data packet and wait for an ACK from the recipient before sending an entire data burst. If the ACK message is successfully received, the sender initiates the TXOP period to transmit the data burst. This protected mechanism helps to avoid bulk data loss due to channel error or multi-user channel contention.



(**a**) Protected Block ACK mechanism



(**b**) Non-protected Block ACK mechanism

Figure 2. Frame aggregation with Block ACK mechanism.

This section presents an analytical model to evaluate the performance of FASBA. A two-dimensional Markov model is used to derive the throughput and end-to-end delays of successful data transmission with the following assumptions listed in Table 3. The developed Markov model is an extension of the Bianchi model [38] under saturated load conditions. We extend the Bianchi model to accommodate frame aggregation and protected block ACK with error-prone channel conditions. In the 802.11 distributed coordination function (DCF), a station with a new packet performs carrier sensing for distributed inter-frame space (DIFS) period and transmits the packet if the channel is idle. If the channel is busy, the station continues monitoring the channel until it becomes free for the DIFS period. Afterwards, the station generates a random backoff period before sending the packet. In saturation load conditions, each station always has a packet available for transmission after the completion of each successful transmission. Moreover, being that all packets are consecutive, the packet needs to wait for a random backoff time before transmitting. The purpose of the random backoff period is to minimise collisions due to multiple users.

Table 3. Markov model assumptions.

Attributes	Value
Number of states	Finite
Load condition	Saturated
Channel condition	Error-prone
Hidden terminals	No
Packet length	Equal

Let us consider $b(t)$ and $s(t)$ to be the stochastic process representing the random backoff counter and backoff stage, respectively. The value of $b(t)$ is decremented at the start of every idle timeslot, and the contending station wins the channel. Then, it reaches zero and can start data transmission according to the basic handshake scheme. To further reduce the chance of collision, the communication parties exchange RTS/CTS control frames to make the surrounding users aware of ongoing communication.

The backoff counter value $k = b(t)$ is chosen from $k \in [0, CW_i]$, where CW_i represents the contention window (CW) size. The collision happens when two stations end up with the same $b(t)$ values. Therefore, the contention window size starts with a minimum value (CW_{min}) and doubles after each unsuccessful transmission. The maximum value of the contention window is $CW_{max} = 2m^{'}CW_{min} = CW_m$, where $m^{'}$ is a positive integer by which the contention window can be doubled and m is used to represent the maximum backoff stage. The value of m is also used to bind the retry limit. If the transmission is still unsuccessful after m retry, the packet will drop and CW will reset. Hence, the channel contention can be described as a two-dimensional Markov chain model with $(s(t), b(t))$.

In this model, every station is modelled by a pair of integers (i, k), where i is the value for the backoff stage and k is the value of the backoff counter. The Markov model is presented in Figure 3. In wireless communication, a station's transmission can fail due to collision with other stations transmitting on the same channel at a given time. Therefore, the probability of collision, p_{coll}, can be written as:

$$p_{coll} = 1 - (1 - \tau)^{n-1} \quad (1)$$

where τ is the transmission probability in a randomly chosen slot time and n represents the number of stations in the medium. In addition to collision, a frame may encounter transmission failure due to fading and/or noise. Thus, the frame failure transmission probability, p_f, becomes:

$$p_f = 1 - (1 - p_{coll})(1 - p_{err}) \quad (2)$$

where p_{err} is the probability of frame error due to the channel condition.

Let us consider that a station has a packet to transmit. Before initiating the transmission, the station will choose a random backoff timer from the window of $[0, CW_{min}]$. The station tried to transmit the frame for the last $(i - 1)$ times but was unsuccessful; the station moves to any state on (i, k) with probability p_f/CW_i. If the transmission is successful at any stage, the station moves to backoff stage 0 with probability $(1 - p_f/CW_0)$. Hence, transition probabilities of the Markov chain can be written as:

$$P(i, k|i, k+1) = 1; k \in [0, CW_i - 2], i \in [o, m]$$

The backoff timer is decremented from $k + 1$ to k when a station has detected an idle time slot.

$$P(0, k|i, 0) = (1 - p_f)/CW_0; k \in [0, CW_0 - 1], \\ i \in [0, m]$$

After successful transmission with probability $1 - p_f$, a station moves from backoff stage i to 0.

$$P(i, k|i - 1, 0) = p_f/CW_i; k \in [0, CW_i - 1], \\ i \in [1, m]$$

At stage $i - 1$, the station attempts to transmit but fails and moves to backoff stage i with a randomly chosen backoff delay.

$$P(m, k|m', 0) = p_f / CW'_m; k \in [0, CW_i - 1]$$

It is the same as number 3, except the station reaches maximum backoff stage m.

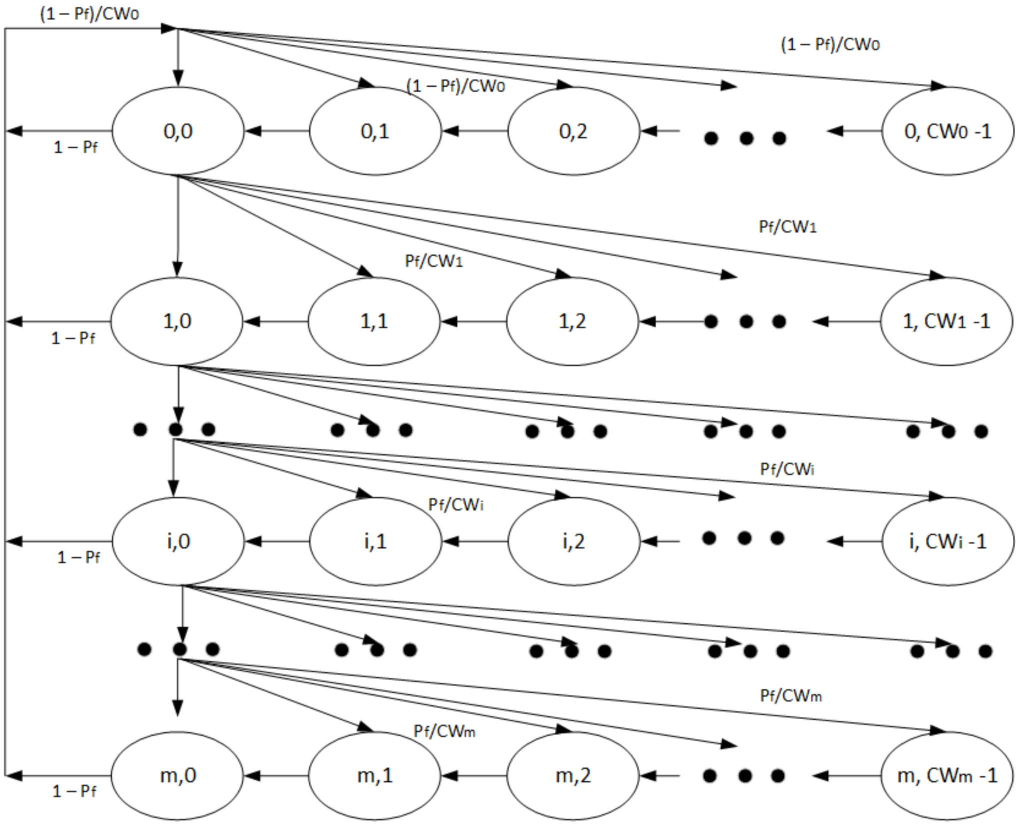


Figure 3. Two−dimensional Markov chain model for FASBA-based 802.11n backoff.

Let $b_{i,k} = lim_{t \to \propto} Ps(t) = i, b(t) = k, i \in (0, m), k \in (0, CW_i - 1)$ be the stationary probability of the chain. Now, using the same reasoning [38], we can estimate the probability of transmission τ at any random slot for both cases when retry limit (m) is smaller than the maximum backoff stage (m').

$$\tau = \frac{2(1 - 2p_f)(1 - p_f^{m-1})}{X} \tag{3}$$

where $X = (1 - p_f)CW(1 - 2p_f^{m+1}) + (1 - 2p_f)(1 - p_f^{m+1})$ and $Y = CW(1 - 2p_f^{m'+1})(1 - p_f) + (1 - 2p_f)(1 - p_f^{m+1}) + 2m'CWp_f^{m'+1}(1 - 2p_f)(1 - p_f^{m-m'})$. When retry limit (m) is greater or equal to the maximum backoff stage, the Equation (3) becomes:

$$\tau = \frac{2(1 - 2p_f)(1 - p_f^{m=1})}{Y} \tag{4}$$

Now, to solve p_f, we first define the probability of frame error p_{err}, which is a combination of the frame error of the MAC data frame (FE_{data}) or ACK frame (FE_{ACK}). Therefore, p_{err} can be expressed as follows:

$$\begin{aligned} p_{err} &= 1 - (1 - FE_{data})(1 - FE_{ACK}) \\ &= FE_{data} + FE_{ACK} - FE_{data} \cdot FE_{ACK} \end{aligned}$$

According to [39], frame error can be calculated based on maximum Doppler frequency (f_d) from station mobility and fading margin (f_m).

$$FE = 1 - exp(-f_m - f_d\sqrt{2\pi\rho T_p}) \tag{5}$$

Now, the solution for the non-linear system represented by Equations (3)–(5) can be solved numerically with two unknown parameters τ and p_f. Knowing τ, we can calculate the probability (P_{tr}) that at least one station transmits a packet in a randomly selected time slot and the conditional probability (P_s) that the occurring packet is successfully transmitted as follows:

$$P_{tr} = 1 - (1-\tau)^n \tag{6}$$

$$P_s = \frac{n\tau(1-\tau)^(n-1)}{1-(1-\tau)^n} \tag{7}$$

4.1. Throughput Analysis

The throughput can be defined as a ratio of the actual amount of data successfully transmitted over a communication link for the length of a randomly chosen time slot, which is:

$$S = \frac{P_{tr}P_s(1 - P_{err}E[P])}{A} \tag{8}$$

where $A = (1-P_{tr})\sigma + P_{tr}P_s(1-p_{err})T_s + p_{tr}(1-P_s)T_c + P_{tr}P_sP_{err}T_e$ and σ represents the backoff slot duration. T_s, T_c, and T_e are the average time for successful transmission when the transmission collides and is wasted due to channel error or fading. For the protected Block ACK scheme, the T_s, T_c, and T_e can be calculated as follows:

$$T_s = T_{ACK} + T_{SIFS} + (T_{data} + T_{SIFS}) \cdot B + T_{bar} + T_{sifs} + T_{ba} \tag{9}$$

$$T_e = T_{hob} + T_{eifs} + (T_{sifs} + T_{hack}) \times \frac{1 - FER_{hob}}{FER_{hob} + FER_{hack} - FER_{hob}FER_{hack}} \tag{10}$$

$$T_c = T_{hob} + T_{eifs} \tag{11}$$

4.2. Mean Delay

The mean delay of a packet consists of MAC delay and queuing delay. The MAC delay is defined as the time taken by the packet to be successfully transmitted with an acknowledgement. In contrast, queuing delay refers to the expected time spent in the queue. This work considers the M/M/1/K queue due to its simplicity and accuracy. The mean packet delay can be calculated as follows:

$$D = \sum_{n=0}^{m}\left[\frac{(p_f^i - p_f^{m+1})((CW_i+1)/2)}{1-p_f^{m+1}}\right] \cdot ((1-P_{tr})\sigma + P_{tr}P_s(1-P_{err})T_s + P_{tr}(1-P_s)T_c + P_{tr}P_sP_{err}T_e + \left(\frac{\rho(1-(K+1)\rho^k) + K\rho^{k+1})}{(1-\rho)(1-\rho^{k+1})}\right) \times \frac{1}{\lambda(1-P_{drop})} \tag{12}$$

where ρ is the steady state condition which is $\frac{\lambda(1-P_{drop})}{\mu}$ and P_{drop} is $[1-(1-p_f)(1-\tau)^{n-1}]^{m+1}$.

5. Performance Evaluation

In this section, the performance of FASBA is evaluated by quantitative stochastic simulation. FASBA's performance is compared with that of MP-EDCA. For system performance evaluation, we consider three important network performance metrics: throughput, packet delay, and packet retransmission attempt.

Simulation Environment

To study the performance of the proposed FASBA and to compare it with MP-EDCA [10], Riverbed Modeler version 18.0 [9] is used. The Riverbed simulation tool was chosen due to its popularity and credibility [40]. For the system performance study, we created about 30 simulation scenarios (15 for FASBA and another 15 for MP-EDCA).

Table 4 shows the MAC parameters used in the simulations. To implement the frame catenation shown in Figure 4, a new data frame is developed with the reserve type field of 11 and a subtype value of 1000 of the frame control field of the MAC frame structure.

Table 4. MAC parameters used in simulation.

General Parameters	Data rate = 65 Mbps (base)/600 Mbps (max) Protocol = IEEE 802.11n Number of MP-EDCA nodes: 4–60 Number of FASBA nodes: 4–60 Application: data (text message of 150 characters) TXOP limit = 0 ms			
Contention Parameters	**MP-EDCA and FASBA**			
	Risk to Life (RtoL) Priority Nodes	Risk to Health (RtoH) Priority Nodes	Risk to Property (RtoP) Priority Nodes	Risk to Environment (RtoE) Priority Nodes
	RtoL SIFS = 10 RtoL Slot Time = 25 AIFS [0] = 1 slot WMin [0] = 2 slots WMax [8] = 8 slots	RtoH SIFS = 25 RtoH Slot Time = 40 AIFS [0] = 1 slot WMin [0] = 2 slots WMax [8] = 8 slots	RtoP SIFS = 40 RtoL Slot Time = 55 AIFS [0] = 1 slot WMin [0] = 2 slots WMax [8] = 8 slots	RtoL SIFS = 55 RtoL Slot Time = 70 AIFS [0] = 1 slot WMin [0] = 2 slots WMax [8] = 8 slots

We implemented a simple two-bit BlockAck request and response frames in the Riverbed Modeler simulator by customising the 802.11 EDCA frames. The implementation involves creating new nodes for network communication and the corresponding process models in the system. The 802.11 WLAN MAC packet formats are categorised into three types i.e., (1) management, (2) control, and (3) data packets. For implementing FASBA in Riverbed Modeler, the type of MAC data (Figure 4) and BlockAck of control packets (Figure 5) were modified. The type bits of the WLAN data packet are used for identifying the packet sequence. And only 4 bits out of 32 bits of the BlockAck field of control packs were used for sending the acknowledgement.

Moreover, EDCA's MAC model was also customised to implement the BlockAck request and BlockAck frames. The activation of FASBA is through the same activation process used in the EDCA, that is, adding a block acknowledgement (ADDBA) frame. In this work, we only considered video traffic and the UDP transmission protocol.

The FASBA's frame aggregation with a block-acknowledge maintains backward compatibility with the existing Distributed Coordination Function (DCF) and EDCA protocols. The general parameters such as area, mobility and channel condition are presented in Table 5. Additionally, while Figure 2 illustrates both protected and non-protected mechanisms, we only simulated the protected mechanism. This is because protection aims to safeguard against bulk data loss caused by channel errors or multi-user contention in the same traffic class.

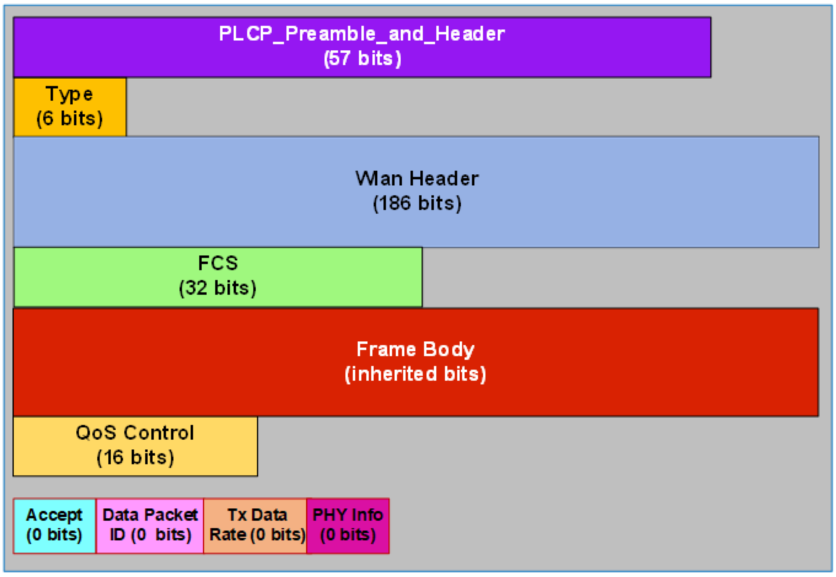


Figure 4. Data packet format of FASBA.

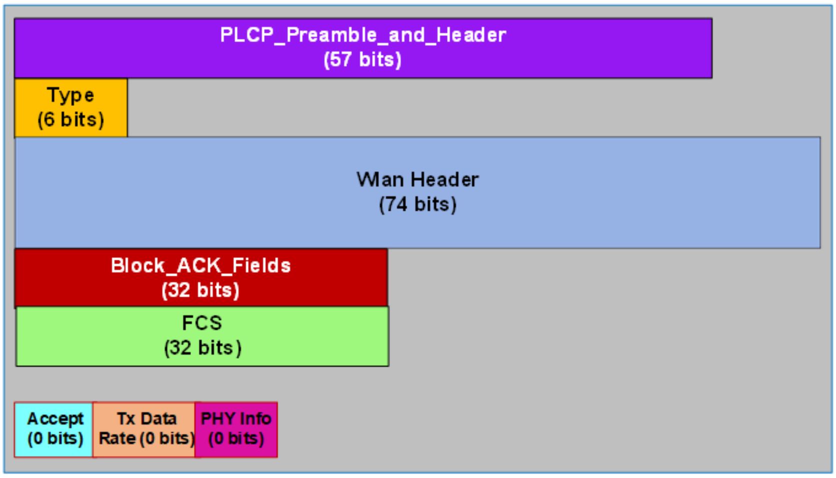


Figure 5. Data packet format of FASBA.

Table 5. General parameters used in the simulation.

Parameters	Value
Area	500×500 m^2
Number of nodes	4–60
Mobility model	Random waypoint
Mobility	7 m/s
Noise figure	5 (high level)

6. Results and Discussion

For both individual stations and the overall network, three important performance metrics are used: (1) throughput, (2) packet delay, and (3) packet retransmission attempt.

6.1. Throughput Performance

In Figure 6, we plot the mean network throughput versus the number of life-saving emergency nodes for the proposed FASBA protocol. We study the network throughput and validate our analytical model developed in Equation (8) using MATLAB 2024a-based simulation. We observe that both the analytical and simulation throughput of FASBA remain the same for emergency nodes up to 24. When the number of life-saving emergency nodes increases from 24 to 60, the analytical throughput (blue line) is slightly lower (up to 5%) than the simulation ones, but these differences are not very significant. A close match of analytical and simulation results validates our analytical model for FASBA life-saving emergency nodes. We consider Figure 6 to validate the simulation results such as throughput, MAC delay, and packet retransmission attempts presented next.

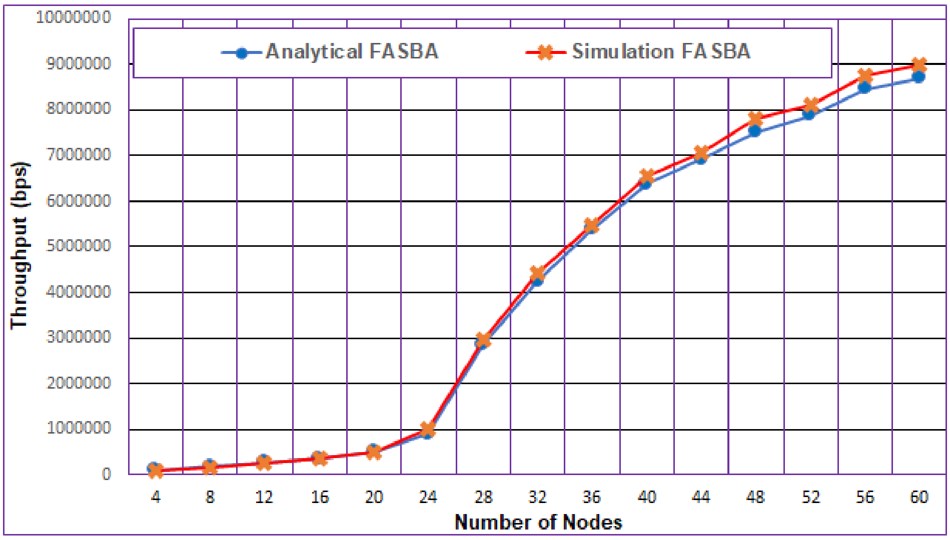


Figure 6. Mean network throughput of the proposed FASBA.

The network throughput versus the number of life-saving emergency nodes of FASBA and MP-EDCA for an ad hoc and infrastructure network are shown in Figures 7 and 8, respectively. One can observe that FASBA provides higher throughput than MP-EDCA irrespective of network architecture, especially under medium- to high-traffic loads. For example, Figure 7 compares mean network throughput (ad hoc network) for N = 4 to 60 emergency nodes. We found that FASBA offers an improved network throughput of up to 10 Mbps for 60 nodes. We also observe that both MP-EDCA and FASBA provide similar throughput performance for N = 4 to 36 nodes. For 40 to 60, FASBA performs much better than MP-EDCA. For example, the proposed FASBA scheme achieved about 17% higher throughput than the MP-EDCA at N= 60 emergency nodes.

Figure 8 exhibits the comparative average network throughput of an infrastructure network. The graphs shown in Figure 8 illustrate that the proposed FASBA offers an improved network throughput of up to 15 Mbps for 60 nodes. Similar to the ad hoc network 6.4(a), both schemes (MP-EDCA and FASBA) provide equal throughput for a number of nodes up to 28. When adding nodes from 32 to 60, FASBA outperforms MP-EDCA. The graph shows that FASBA achieves up to 17.5 % higher throughput than the standard MP-EDCA. Moreover, one can observe that the average network (ad hoc network) throughput constantly increases with the increasing number of nodes.

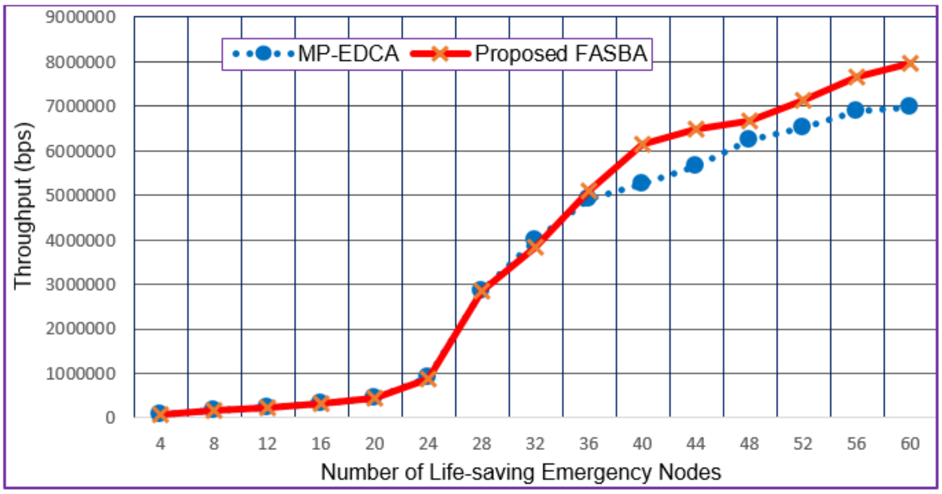


Figure 7. Mean network throughput of MP-EDCA and the proposed FASBA (ad hoc network scenario).

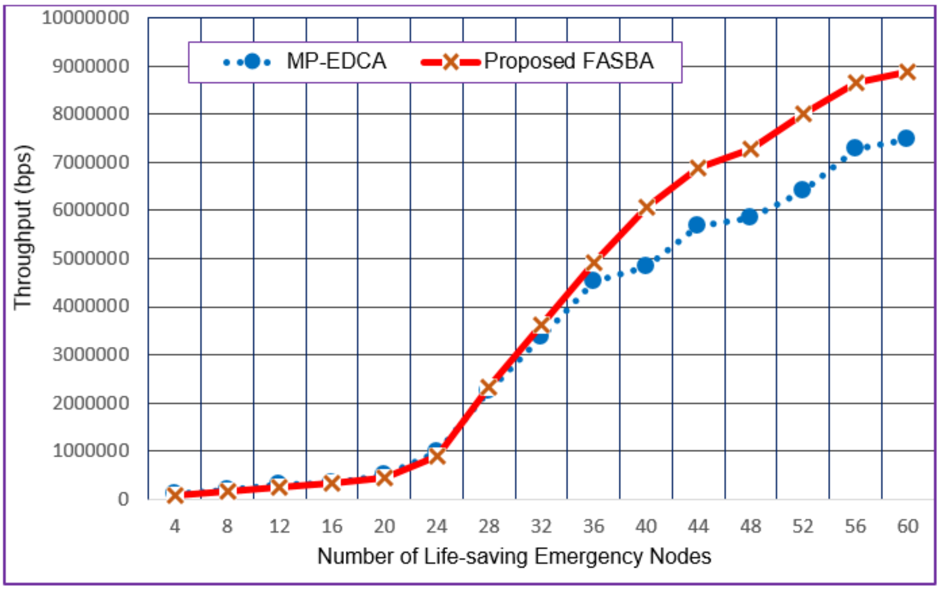


Figure 8. Mean network throughput of the proposed FASBA (infrastructure network scenario).

6.2. Mean Delay Performance

The mean delay is a summation of the MAC layer delay and the delay due to time spent in the queue before the actual packet transmission. Figure 9 represents the mean delay for the proposed FASBA protocol.

The mean packet delays of FASBA in an ad hoc network for N = 60 nodes is shown in Figure 10. One can observe that FASBA outperforms MP-EDCA for N = 24 to 60 nodes. For example, FASBA's mean packet delay is about 30% lower than MP-EDCA for a network with N = 60 nodes.

Both emergency traffic and time-sensitive applications are delay-sensitive. It is found that FASBA can support up to 32 emergency nodes, whereas MP-EDCA can support about 24 nodes. It is observed that FASBA's mean delay is lower than MP-EDCA in both ad hoc and infrastructure networks.

The main conclusion that can be drawn from Figure 10 is that nodes using FASBA have substantially lower mean packet delays than the nodes using MP-EDCA, especially under medium- to high-traffic loads.

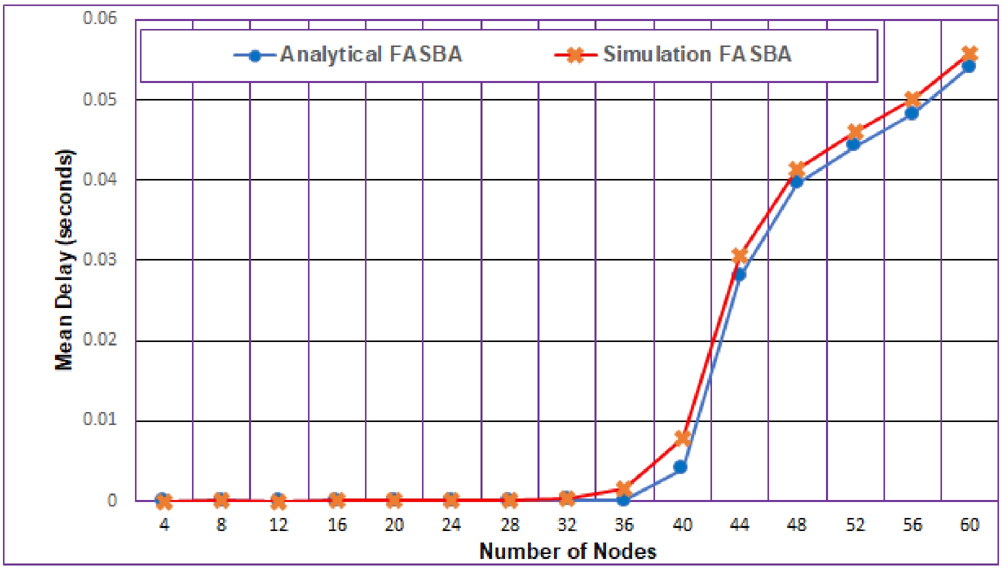


Figure 9. Mean MAC delay performance of the proposed FASBA.

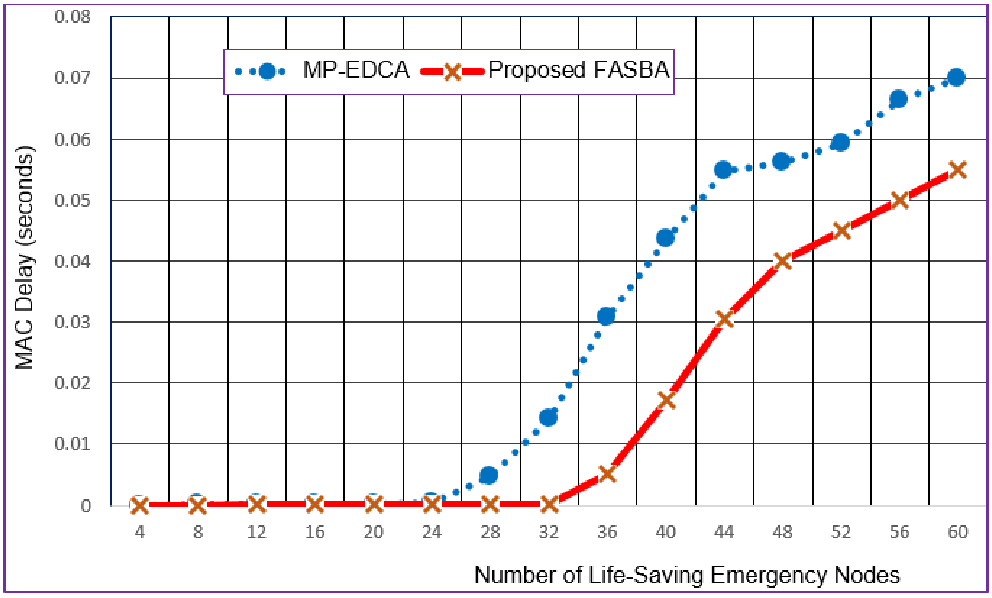


Figure 10. Mean MAC delay performance of MP-EDCA and the proposed FASBA.

6.3. Packet Retransmission

Figure 11 shows the number of retransmitted packets for MP-EDCA and FASBA considered in the simulation. As shown in Figure 11, the proposed FASBA achieves lower retransmission attempts. If we look closely at Figure 11, we observe that the number of retransmitted packets increases with the increase in nodes for both schemes. The proposed FASBA achieved 60% lower retransmitted packets than MP-EDCA. This is achieved by optimising the block acknowledgement mechanism. The proposed FASBA can be used in wireless networks to achieve efficient retransmission. We didn't vary the mobility and channel configuration throughout. Therefore, the changes in retransmission are mainly due to channel contention of several emergency nodes.

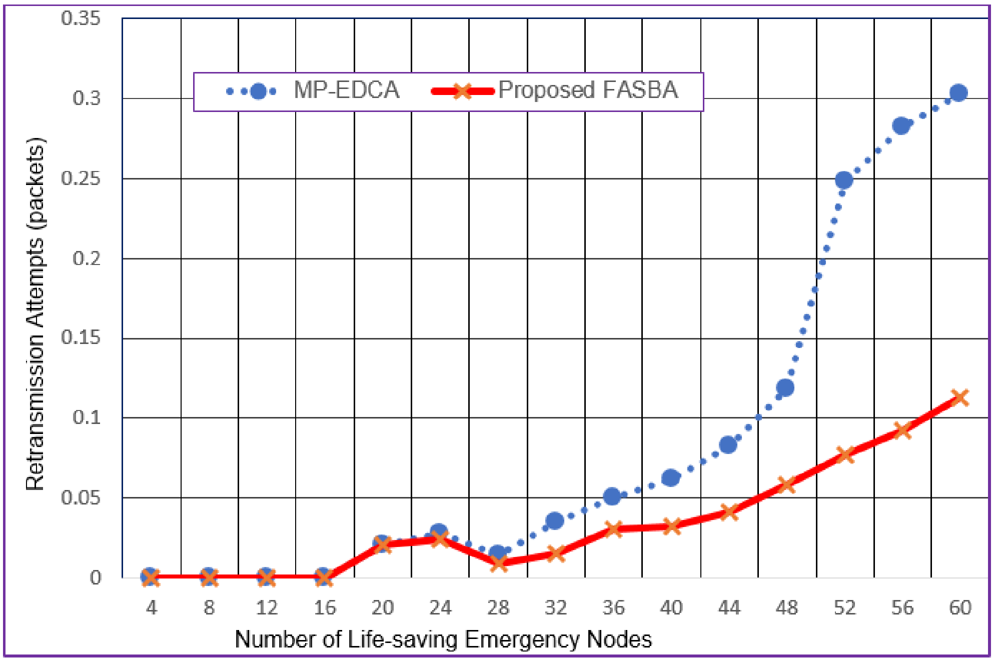


Figure 11. Packet retransmission attempts versus the number of emergency nodes.

7. Conclusions

In this paper, we propose a frame aggregation with a simple block acknowledgement (FASBA) scheme. The FASBA extends the capabilities of MP-EDCA by accommodating an increased number of emergency nodes during emergency times. The FASBA's throughput and packet delays are improved by significantly reducing transmission overheads. The overheads are reduced by aggregating frames with a simple block acknowledgement mechanism before transmission. Consequently, FASBA offers a guaranteed service delivery in highly loaded networks.

Riverbed Modeler and MATLAB 2024a-based simulation models validate the system performance. The results obtained have shown that FASBA achieves about 30% lower packet delays, 17% higher throughput, and 60% lower retransmission attempts than MP-EDCA. Therefore, FASBA can be used to provide a strict QoS guarantee for life-saving emergency nodes. The findings reported in this paper provide insights into QoS guarantee for life-saving emergency traffic that can help network researchers and engineers contribute further towards developing next-generation wireless networks. In our future works, we will further investigate the impact of different traffic types and transmission protocols on FSBA performance. Moreover, the number of frames that can be aggregated is still an open issue to investigate to identify the optimum solution for frame aggregation. However, incorporating FASBA into the design of the Internet of Things to save human lives in emergency times is suggested as future work.

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