Preemptive Admission Control Mechanism for Strict QoS Guarantee to Life-Saving Emergency Traffic in Wireless LANs

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Abstract— The increasing usage of distributed emergency services (e.g. natural disaster or disaster caused by humans) in wireless local area networks requires the support of immediate channel access with strict quality of service (QoS) guarantee from a medium access control (MAC) protocol. The IEEE 802.11e/enhanced distributed channel access (EDCA) standard is the MAC enhancement for QoS. Unfortunately, 802.11e (EDCA) neither supports emergency traffic nor provides a strict QoS guarantee especially for a large number of users who report an emergency. To address this problem of achieving a strict QoS guarantee for emergency traffic, we previously developed and reported a multi-preemptive EDCA (MP-EDCA) protocol suitable for operating under low to medium traffic loads. However, MP-EDCA does not provide a strict QoS guarantee to life-saving emergency traffic (e.g. ambulance calls) in highly loaded networks. In this paper, we provide a solution to the problem of achieving a strict QoS guarantee to life-saving emergency traffic under high traffic loads. To this end, we propose a preemptive admission control (PAC) mechanism for MP-EDCA called PAC-MP-EDCA. The proposed PAC-MP-EDCA protects ongoing life-saving emergency traffic flows by giving high priority; thus, assures a QoS guarantee (in terms of lower packet delays) to life-saving emergency traffic when a high number of nodes require immediate channel access during emergency time. The priorities are set by carefully adjusting the short inter-frame space and slot-time in the emergency frames. The performance of PAC-MP-EDCA is evaluated by Riverbed Modeler simulation. Results obtained show that the proposed PAC-MP-EDCA achieved up to 98% lower MAC delays for life-saving emergency nodes and about 15% higher throughput than MP-EDCA under high traffic loads.

Index Terms— Preemptive Admission Control (PAC), QoS, Multi-preemptive EDCA, MAC, Performance evaluation.

1. Introduction

There has been tremendous growth in the deployment of IEE 802.11-based wireless local area networks (WLANs) especially for use in distributed emergency applications (e.g. health monitoring, disaster recovery, and surveillance) [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 IEEE 802.11e [5] standard was introduced to improve QoS for real-time traffic, such as voice and video. Specifically, the 802.11e medium access control (MAC) protocol or Enhanced Distributed Channel Access **(**EDCA) provides relative service differentiation into eight levels of service priority 0 to 7 (0 represents low priority and 7 is high priority). The voice traffic is given a priority of 6 or 7; video is 4 or 5; best-effort traffic 0 or 3; and the background traffic priority is 1 or 2 [6]. Each priority represents a level of service that provides differentiated channel access depending on traffic type. For example, voice traffic is transmitted with a high priority than low priority best-effort traffic such as email and FTP. However, EDCA neither supports emergency traffic (which requires in-channel preemption with priority channel access) nor assures the QoS guarantee requirements concerning packet delays, throughput, and packet losses in highly loaded networks [7].

We have looked at various literature on the latest release of IEEE 801.11e/EDCA and found the 2007 amendment, the most recent after Release 2005 [https://en.wikipedia.org/wiki/IEEE_802.112005#Enhanced_distributed_channel_access_(EDC)]

In IEEE 802.11-2007 amendment, MAC schemes, such as Enhanced distributed channel access (EDCA) and HCF Controlled Channel Access (HCCA) remain the same as Release 2005. However, automatic power save delivery and Block acknowledgments features are incorporated in Release 2007. In our study, we consider EDCA/802.11e QoS, and therefore both Release 2005 and 2007 are equally applicable. To overcome the limitations of EDCA, previously we proposed and reported a multi-preemptive EDCA (MP-EDCA) for WLANs [8]. While MP-EDCA supports emergency traffic and a provision of in-channel preemption, it does not assure a QoS guarantee to life-saving emergency traffic especially in an overloaded network.

In this paper, we explore the adaptation of the well-known ‘admission control’ approach in managing QoS guarantees to life-saving emergency traffic. To this end, we develop a preemptive admission control (PAC) mechanism to address the performance degradation issue of MP-EDCA. Our new PAC approach (called PAC-MP-EDCA) provides a strict QoS guarantee to life-saving emergency traffic where a large number of nodes require immediate channel access, especially during an emergency time. This strict QoS guarantee is achieved by protecting ongoing life-saving emergency traffic flows by giving them high-priority channel access. The channel access priorities are set by carefully adjusting parameters, such as short inter-frame space (SIFS) and slot-time in the emergency frames. The proposed PAC-MP-EDCA mechanism is based on channel capacity analysis. The maximum number of high-priority traffic flows is determined by the capacity analysis. We develop emergency communication nodes and process models to implement PAC-MP-EDCA in Riverbed Modeler (formerly OPNET) simulator for system performance study [27].

The main contributions of this study are summarized as follows.

- We propose a preemptive admission control (PAC) mechanism to provide a solution to the problem of achieving a strict QoS guarantee to life-saving emergency traffic in high loads. To this end, we implement (in C++) a life-saving emergency communication node and the corresponding process model in the Riverbed Modeler simulator for system performance study and comparison. This is a significant piece of work contributing towards the implementation of emergency traffics in next-generation WLANs.
- We analyze and validate the performance of the proposed PAC-MP-EDCA by comparing it with the standard IEEE 802.11e (EDCA) and the previous study (MP-EDCA). To this end, we provide a mathematical framework for capacity analysis of Emergency Traffic which forms the basis of PAC-MP-EDCA design and evaluation (Section 3).
- We develop a queuing model and derive mean packet delays analytically to estimate the system performance. We then perform an extensive simulation (about 45 simulation scenarios) to validate the performance of the proposed PAC-MP-EDCA.

The rest of this paper is organized as follows. The admission control approaches and related work are presented in Section 2. The system capacity analysis and queueing model are presented in Section 3. The proposed PAC approach is described in detail in Section 4. The system simulation modeling and results are presented in Section 5. Finally, the paper is concluded in Section 6. Table 1 list the abbreviations used in this study.

Table 1: List of abbreviations

Abbreviation	Definition	Abbreviation	Definition
AIF	Arbitration Inter-frame Spacing	IFS	Inter-frame Space
AC	Admission Control	MAC	Medium Access Control
ACM	Admission Control Mandatory	MSDU	MAC Service Data Unit
BSS	Basic Service Set	MP-EDCA	Multi-Preemptive EDCA
CP-EDCA	Channel Preemptive EDCA	PAC	Preemptive Admission Control
CW	Contention Window	PRED	Priority Random Early Detection
CFB	Contention Free Bursting	SIFS	Short Inter-frame Space
EDCA	Enhanced Distributed Channel Access	TXOP	Transmit Opportunity
EDCA-DRR	EDCA-Distributed Resource Reservation	PDF	Probability Density Function
EDCA-RR	EDCA with Resource Researvation	802.11	IEEE 802.11 Standard
FMM	Feedback Monitoring Module	WLAN	Wireless Local Area Network
FTP	File Transfer Protocol	FRRBC	Fair round robin binary countdown

2. Related Work

The admission control technique is useful to handle network congestion and to provide a QoS guarantee [9]. For instance, a typical WLAN can be set up to administer network policies and to regulate available bandwidth ensuring that time-sensitive applications meet QoS requirements [10].

There are two distinct admission control mechanisms. One is based on contention-based access, and the other one is based on controlled access. Admission control, in general, depends on vendors' implementation of the scheduler, available channel capacity, link conditions, retransmission limits, and the scheduling requirements of a given stream [11]. One of the main limitations of 802.11e (EDCA) is that it does not provide QoS guarantees under medium to high traffic loads [12]. To overcomes this limitation, many network researchers have proposed schemes to provide QoS guarantees using admission control. Son, S. et al. [13] proposed an admission control with adaptive arbitration inter-frame spacing (AIF) mechanism to address the QoS guarantee in EDCA. Admission control limits the traffic flows based on network capacity and adaptive AIF is used to priorities high-priority traffic. This scheme, however, provides differentiation of services near to absolute priority for high priority traffics.

Xiao, Y. et al. [14] adopted two-level protection technique to guarantee bandwidth for time-sensitive applications. The guaranteed bandwidth is achieved using distributed admission control and a tried-and-known mechanism. The distributed admission control measures the channel utilization on each beacon interval, and the available capacity/budget is estimated. traffic streams will not get transmission slot/opportunity if their class capacity is zero. Furthermore, nodes are not allowed to increase their transmission time. However, a new flow is first temporarily accepted and then measure network performance for some beacon intervals. The flow is rejected if it affects the performance and not on the specific requirements. Chen et al. [15] also proposed two schemes: call admission mechanism and rate control mechanism. The call admission control is for real-time traffic and rate control for best-effort traffic. Rate control utilizes the remaining channel capacity without affecting the time-sensitive traffic; each node monitors the channel busyness ratio and estimates the rate of the ongoing real-time traffic before adding the traffic. Hamidian, A. et al. [16] developed EDCA with resource reservation (EDCA-RR). The authors proposed a traffic scheduler and admission control mechanism. Before admitting the time-sensitive traffic stream; it is necessary to calculate the schedule service interval and resource reservation (RR). Hamidian, A. et al. enhanced EDCA-RR [16] and proposed an EDCA-distributed resource reservation (EDCA-DRR) scheme that used distributed approach for the same admission control, traffic scheduling, and resource reservation.

Yang et al. [18] investigated priority random early detection (PRED) mechanism by enhancing random early detection (RED) [19]; PRED alters queue[AC] based on traffic load used scheduling mechanism to give priority to each packet within the node. Sarma et al. [20] proposed a strict priority-based QoS-aware protocol (SPQAMP) that gives priority to a time-sensitive node to send the packet by assigning non-overlapping values to CW for time-sensitive and best effort traffics, and reset the back-off counter instead of freezing best-effort traffic.

Centikaya [21] developed admission control, flow-based, and class-based queuing schemes to provide QoS to different time-sensitive applications. Furthermore, each node alters the back-off counter based on the node's own packet's priority and previously transmitted packet's priority to protect time-sensitive traffic. Tadayon, N. et al. [22] addressed the inefficiency of uniform probability density function (PDF) used in EDCA while dealing with new time-sensitive applications. They replace Uniform with Gamma PDF to priorities the time-sensitive applications.

Table 2: Summary of related work on QoS guarantee in WLANs

Researcher	Contribution	Key concept / description	Limitation
Xiao, Y. et al. [14]	Providing QoS guarantee to voice and video	Introduced distributed admission control and tried-and-know mechanism to provide QoS guarantee to voice and video.	Changing window size for deferring node transmission.
Chen, X. et al. [15]	Improving QoS guarantee to real-time traffic	Proposed two schemes; call admission control for high priority and rate control for low priority traffic.	Not improving QoS for other traffics.
Hamidian, A. et al. 2006 [16] and 2008 [17]	Proposing EDCA-RR and EDCA-DRR	Investigated admission control and real-time traffic reservation channel. The problem of hidden nodes and TXOP was addressed.	All traffic has the same priority, not capable of prioritizing traffics.
Yang, C. et al. [18]	Proposing PRED	Enhanced in the previously proposed mechanism by Floyd, S. et al. [82] to provide a better QoS guarantee.	Scheduling mechanism to give priority.
Sarma, N. et al. [20]	Proposing SPQAMP	Improved QoS guarantee by providing non-overlapping CW to time-sensitive traffic.	Static CW assigned to time-sensitive traffic. Not perform well in medium-high traffics.
Cetinkaya, C. [21]	Providing QoS to real-time traffic	Proposed three schemes (admission control, flow-based, and class-based queuing) to prioritize the traffic.	Provide limited QoS for IP networks. Difficult to implement.
Tadayon, N. et al. [22]	Improving QoS guarantee	Achieved QoS guarantee by tuning CW based on channel load.	Replacement for Uniform PDF by Gamma PDF.
Ferng, H. et al. [23]	Introducing FRRBC	Investigated QoS guarantee with fairness.	Multiple mapping to fixed-bit binary numbers for priorities.
Mansoor, et al. [24]	Proposing FACU	Proposed the feedback-based admission control unit (FACU).	FACU exploits information piggybacking.

Pang et al. [25] investigated a joint measurement-based admission and bandwidth control (JMABC). JMABC protects the ongoing traffic stream from upcoming traffic streams through a measurement-based admission control scheme. Moreover, JMABC priorities real-time traffic using the packet scheduling scheme. All incoming packets from other stations are first admitted by admission control and forwarded to Adaptive Class-Based Queue (ACBQ). ACBQ is monitored by the feedback monitoring module (FMM) database. FMM determines the ACBQ's throughput and system's total throughput and provides the feedback back to admission control. JMABC may provide QoS guarantee to real-time traffic, however, the cost of the operation of JMABC may highly affect the system performance.

A review of literature on admission control methods in providing QoS guarantee in WLANs is summarized in Table 2. Most of the admission control schemes reviewed in this section focused on the service differentiation aspect of QoS especially operating under low-to-medium traffic loads [26]. The work on supporting a strict QoS guarantee to life-saving emergency traffic under high traffic loads has not been fully explored yet. The proposed PAC-MP-EDCA mechanism described in Section 4 provides a solution to strict QoS guarantee to life-saving emergency traffic in high loads.

3. System Capacity Analysis

3.1 Capacity Analysis of Emergency Traffic

The proposed PAC-MP-EDCA addresses the performance degradation issues of MP-EDCA and provides a strict QoS guarantee to life-saving emergency traffic in highly loaded networks. The PAC-MP-EDCA is based on the capacity analysis of emergency traffic. Among the four different types of emergency traffic, the admission control is applied to life-saving (i.e. Risk to life) emergency traffic. The capacity analysis approach presented in this section is adapted from [13]. The main difference is that admission control reported by Sunghwa, S. et al. [13] is limited to low priority traffic, whereas admission control reported in this paper is focused on high priority life-saving emergency traffic which is activated dynamically when the network load is reached at the network capacity. Another difference is that the design of PAC-MP-EDCA is based on MP-EDCA described in [8].

The high-priority emergency traffic is delivered timely due to MP-EDCA's preemptive characteristics. The problem occurs when the same priority traffic wants to access the medium in a saturated situation which increases the collision and degrade the system performance. The proposed PAC algorithm (Section 4.3) analyses the network capacity to protect the existing (ongoing) flows of life-saving traffic from low or same priority emergency traffic specifically in saturated network conditions. This ensures that the system only admits new traffic flow if there is sufficient network capacity. The mathematical framework for capacity analysis of Emergency Traffic is presented next.

Mathematical Framework for Capacity Analysis of Emergency Traffic: To analyze the network capacity for emergency traffic, we followed a similar approach reported in [28]. Among the four priority nodes (Risk to Life: RtoL, Risk to Health: RtoH, Risk to Property: RtoP, and Risk to Environment: RtoE), let us consider Risk to Life (RtoL), i.e. life-saving emergency node only. So, the analysis and system model is based on RtoL.

For n $RtoL$ nodes within the BSS, let the probability of the network state as a fraction of transmitting time of node k be denoted by ρ_k. The idle channel time is denoted by ρ_0. Furthermore, the ratio of the expected transmission time $\epsilon[\varphi_k]$ to the expected back-off time $\epsilon[\psi_k]$ for transmitting node k be denoted by $\mu_k = \epsilon[\varphi_k]/\epsilon[\psi_k]$.

The total number of transmissions by $RtoL$ node k are represented by $c_k(t)$. In the network scenario, if the channel is idle and all the $RtoL$ nodes waiting for the channel would decrease the back-off counters.

Thus, the ratio of ρ_k to ρ_0 can be represented as:

$$\frac{\rho_k}{\rho_0} = \lim_{t\to\infty} \frac{\frac{1}{t}\sum_{j=1}^{c_k(t)} \varphi_k(j)}{\frac{1}{t}\sum_{j=1}^{c_k(t)} \psi_k(j)} = \lim_{t\to\infty} \frac{\frac{1}{c_k(t)}\sum_{j=1}^{c_k(t)} \varphi_k(j)}{\frac{1}{c_k(t)}\sum_{j=1}^{c_k(t)} \psi_k(j)} = \frac{\epsilon[\varphi_k]}{\epsilon[\psi_k]} = \mu_k \tag{1}$$

Where $\psi_k(j)$ represents the length of the j-th back-off interval of $RtoL$ node k and $\varphi_k(j)$ is the length of jth transmission of $RtoL$ node k. From Equation (1), a system of the linear equations may be defined as follows.

$$\rho_\emptyset = \frac{\rho_1}{\mu_1} = \frac{\rho_2}{\mu_2} = \cdots = \frac{\rho_n}{\mu_n} \tag{2}$$

As $\sum_{k=0}^{n} \rho_k = 1$, the above equation can be solved as follows:

$$\rho_\emptyset = \frac{1}{1+\mu_1+\mu_2+\cdots+\mu_n}, \quad \rho_k = \rho_\emptyset \mu_k \tag{3}$$

We consider that MPDU of $RtoL$ node k consists of a MAC header (where the MAC header includes a frame check sequence). Let, the payload be transmitted at the rate of δ_k, the PHY header consists of preamble and acknowledgment frames, and are transmitted at the ratio of $\delta_{min} (\leq \delta_k)$, which does not depend on δ_k, in case of reliable transmission. Moreover, T_{PH}, T_{MH}, T_{PL}, and T_{ACK}

is the time for transmitting the complete frame i.e., PHY header, MAC header, payload, and ACK. The transmission rate of node k to transmit a packet is denoted as $\overline{\delta_k}$, can be expressed as:

$$\overline{\delta_k} = \omega_k \delta_k + (1 - \omega_k)\delta_{min}, \tag{4}$$

where $\omega_k = \frac{(T_{MH}+T_{PL})}{(T_{PH}+T_{MH}+T_{PL}+T_{ACK})}$.

As T_{SIFS} is negligible as compare to T_{PL}, thus is not considered in the calculation of $\overline{\delta_k}$. herefore, x_k, the achievable throughput of saturated node k, is given as:

$$x_k = \rho_k \overline{\delta_k} = \left(\frac{\mu_k}{1+\mu_1+\mu_2+\cdots+\mu_n}\right)\overline{\delta_k}, \tag{5}$$

Based on the above capacity analysis, a simple admission control for $RtoL$ emergency traffic is designed. We consider that a node with $RtoL$ emergency traffic first sends a request for admission to the central coordinator node. After receiving the request, the central coordinator node may send the admission response with acceptance or rejection.

Discussion and Interpretation:

Let n_{RtoL} and v_{RtoL} be the total number of ongoing $RtoL$ nodes, the maximum number of allowable $RtoL$ nodes is based on the capacity analysis (e.g. N = 60 Life-saving emergency nodes). The central coordinator node receives the admission request, the central coordinator node accepts the request as long as

$n_{RtoL} < v_{RtoL} - \Delta v_{RtoL}$

where Δv_{RtoL} is a positive integer number.

Here, Δv_{RtoL} is used for modeling error of capacity analysis into consideration. Once the $RtoL$ emergency traffic stream is admitted, the central coordinator node updates n_{RtoL} . In case, central coordinator node does not receive any traffic from the connected $RtoL$ node for a given time, that is, generally more than the packet generation interval of the $RtoL$ application. Then, the central coordinator node (“central node”) shall consider the connection is lost, therefore, decrease the n_{RtoL} by 1. In this process, the central node will not involve in computing the probability or rates in Equations (1) to (5) to estimate the ν_{RtoL}, which can be estimated by the traffic model of $RtoL$ node. Therefore, there are no computational costs for this admission control.

The achievable throughput in (5) is taken without estimating the collision, the assumption is that the central coordinator node will not admit new $RtoL$ nodes exceeding the system capacity. The central node maintains the number of $RtoL$ connections at the given time for managing the network capacity. Since multiple $RtoL$ nodes simultaneously access the medium and because of collision. Therefore, to minimize the probability of collisions, the admission delaying techniques may be incorporated in the central coordinator node.

For example, υ_{int} as the interval for generating packet of $RtoL$ node, and τ_k is a time when the $RtoL$ connection i is admitted. The $\Delta\tau_k(> 0)$ as the offset timing of $RtoL$ connection k within υ_{int} $\Delta\tau_k = mod(\tau_k, \upsilon_{int})$ where $mod(x, y)$ is a modulus function that divides x by y and returns modulo. If the central coordinator node receives a new admittance request for $RtoL$ node at the time of τ_k, it calculates the difference between $\Delta\tau_m$ and $\Delta\tau_k(\forall k \neq m)$.

If the calculated difference is lower than $CW_{RTOL} \cdot \varphi_{slot}$ for any $k \neq m$, the central coordinator node may not respond to the admission request and delay the admission by a certain time while $d(> 0)$, where:

$$\Delta\tau'_m = mod(\tau_m + d, \varphi_{int})$$

$$\underset{\{k\neq m\}}{\text{Min}} |\Delta\tau'_m - \Delta\tau_k| > CW_{RTOL} \cdot \varphi_{slot} \tag{6}$$

Then, the central coordinator node updates the offset timing of $RtoL$ connection m as the updated value of $\Delta\tau'_m$. Moreover, the central coordinator accepts the $RtoL$ node admission request if no any $RtoL$ node is satisfying (6).

The admission request from $RtoL$ nodes may come at a random time. Therefore, the probability is negligible. The ν_{RtoL} are a few tens, φ_{int} is a hundred milliseconds and $CW_{RTOL} \cdot \varphi_{slot}$ is less than 1ms. Therefore, the mean packet delay for admitting the new $RtoL$ node at the central coordinator is estimated according to (6).

4. Proposed Preemptive Admission Control Mechanism

4.1 Revisiting MP-EDCA Protocol

In a separate contributed paper we reported MP-EDCA [8]. The idea was to support life-saving emergency traffic for a large number of nodes that report an emergency.

4.1.1 Emergency Traffic Defined

MP-EDCA supports four classes (Class 1 to 4) of emergency traffic (per node) through four emergency priority queues. Non-priority traffic (e.g. email) is served through a separate queue. The Class 1 emergency traffic (Risk to Life or life-saving emergency) streams have the highest priority, followed by Class 2 (Risk to Health), Class 3 (Risk to Property), and Class 4 (Risk to Environment). Each high-priority emergency traffic stream can preempt the low-priority one to acquire the channel. These four classes of emergency traffics are considered in MP-EDCA based on networking literature as most of the organizations have categorized emergency into four classes, namely life, health, property, and environment [9, 10]. The above four classes of emergency traffics have practical implications in real-life scenarios. For instance, a life-saving emergency (Class 1) has the highest priority because nothing is more important than human lives. This is followed by service prioritization to health, property, and the environment. The priorities are set by carefully adjusting the SIFS and slot-time in the emergency frames.

4.1.2 Limitations of MP-EDCA

The main problem of MP-EDCA is that it does not provide a strict QoS guarantee to life-saving emergency traffic under high traffic loads. We now present simulation results (Figs. 1 and 2) to demonstrate that MP-EDCA fails to provide a strict QoS guarantee for $N > 40$ nodes suggesting that MP-EDCA requires a significant improvement.

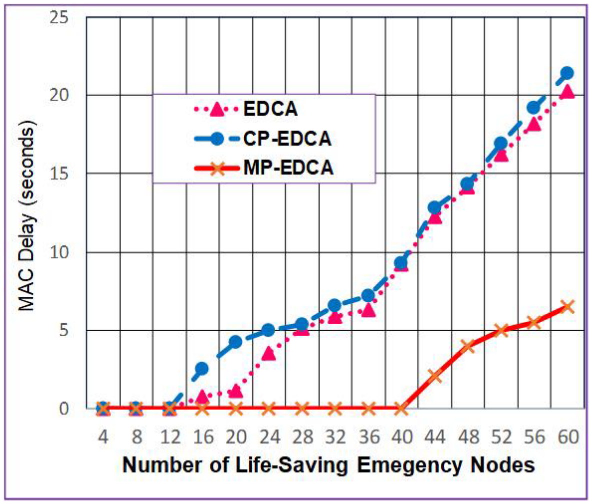


Figure 1: MAC delays versus Life-saving emergency nodes of MP-EDCA, CP-EDCA, and EDCA.

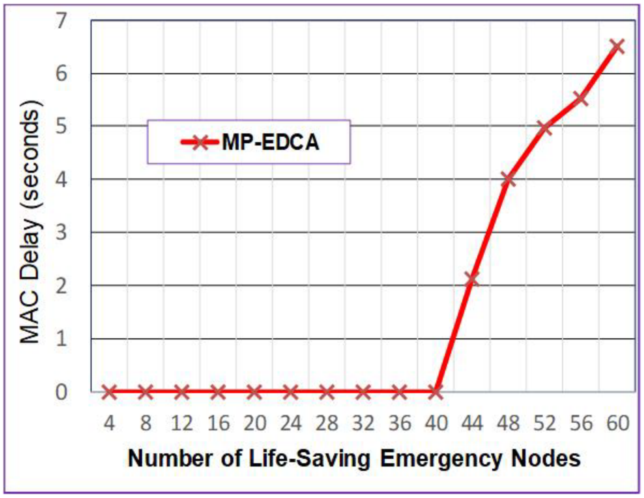


Figure 2: Expanded version of Fig. 1 for clear illustration of MAC delays of MP-EDCA for life-saving emergency node.

The simulation results are presented in Figs. 1 and 2 are the new set of results that are not included in the published paper [8].

For the MP-EDCA performance study, we develop a simulation model (using Riverbed Modeler) with various network Scenarios. In the simulation, we consider uniform node distribution and use the same set of simulation parameters as used in [8] for comparison purposes. We measure network-wide mean packet delays for life-saving emergency traffic by varying node density from 4 to 60. The key research findings are presented in Fig. 1. Figure 2 is redrawn as a zoomed view of Fig. 1 for a clear illustration of MAC delays of MP-EDCA.

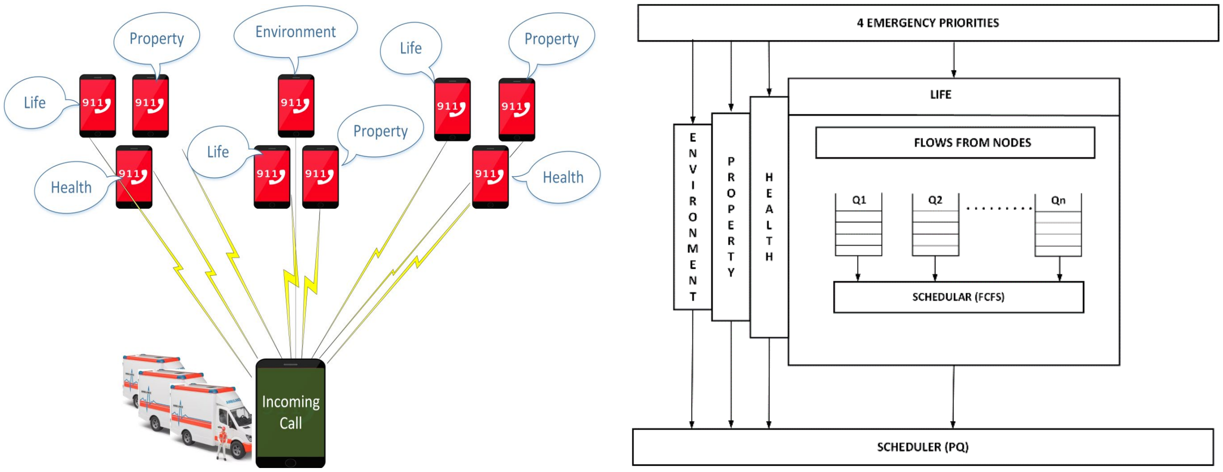
The MAC delays of the standard 802.11e/EDCA and CP-EDCA are also shown for comparison purposes. The CP-EDCA protocol [34] is included in the study because it is a class of preemptive channel access protocols. MP-EDCA was developed to overcome the limitations of CP-EDCA. By looking at Figs. 1 and 2, one can observe that MP-EDCA accommodates a greater number of emergency nodes than EDCA and CP-EDCA. However, the MAC delays of MP-EDCA for life-saving emergency nodes are increasing significantly for N > 40 nodes.

The main conclusion is that MP-EDCA does not provide a strict QoS guarantee (in terms of packet delays) to life-saving emergency traffic when the number of nodes in the network exceeding 40. The proposed PAC-MP-EDCA approach described in the next section provides a possible solution in achieving a strict QoS guarantee to life-saving emergency traffic under high loads.

4.2 The PAC Approach

The main motivation of designing the preemptive admission control (PAC) mechanism is to apply it to MP-EDCA [8] to overcome the problems of achieving strict QoS guarantees for life-saving emergency nodes in dense emergency time where a large number of nodes report an emergency. The resulting proposed protocol is called PAC-MP-EDCA. The PAC-MP-EDCA is based on the capacity analysis of life-saving emergency traffic described in Section 3.1.

The PAC-MP-EDCA protects high-priority traffic from low-priority ones. In many cases, it protects high-priority traffic from being degraded by other traffic of the same priority. In MP-EDCA, admission control is not required to protect high-priority traffic from the low-priority one due to its preemptive nature. However, it may require protecting high-priority life-saving emergency traffic from other same priority traffic. In this section, a detailed EDCA model-based admission control is presented. It is based on the specifications from the 802.11e standard [5]. The proposed scheme defines the action to be taken by the admission controller and the emergency node when a new flow starts/departs or the WLAN state changes. The PAC mechanism is assumed to be implemented at the emergency nodes or access points (APs). The simulation scenario of PAC-MP-EDCA is shown in Fig. 3(a) and the corresponding queueing model is shown in Fig.3(b). The nodes with red color represent the first responders in an emergency and the nodes with green color represent the resources. The green color node act as an AP. All other nodes are looking forward to the green node for the resources.



(a) (b)

Figure 3: PAC-MP-EDCA Model (a) Simulation Scenario; (b) Queuing model

The AP advertises admission control mandatory (ACM) bit for life-saving traffic category using the Beacon to indicate that admission control is mandatory for life-saving emergency traffic. The node with life-saving emergency traffic sends Add Traffic Stream (ADDTS) request action frame to AP that includes a Traffic Specification (TSPEC). The parameters for PAC include a MAC Service Data Unit (MSDU) size, data rate, physical rate, and surplus bandwidth allowance (SBA). Once the AP receives ADDTS request, AP runs the PAC algorithm and communicates back to the emergency node with the admittance decision using ADDTS response action frame. Furthermore, to provide a privilege to high priority emergency traffic to preempt the low priority one.

Referring to the queuing model as shown in Fig 3b, there are four access classes (ACs) namely, Life, Health, Property, and Environment in the system. Each AC maintains its queue. Figure 3(b) shows the priority queue (PQ) for life-saving AC. A first come first serve approach is used for the traffic of the same AC. When the queue is full, the newly arrived packets will be dropped out. Each AC will then follow the preemptive PQ mechanism as per Algorithm 1 (Section 4.3).

In this research, we consider M/D/1/K queuing system. It is widely studied to model a system in which customer or packet arrival rate follows a Poisson distribution with deterministic (e.g. fixed) service time (μ). This is an appropriate approach for the scenario presented in Fig 3(a) where the arrival rate of any emergency call is Poisson which requires a fixed number of timeslots () to complete the transmission. This queuing model has a single channel with a finite capacity of (k-1) places in the queue. Hence, any packets that arrive after the queue is full will be dropped. However, we consider M/D/1/K/PQ to determine the packets that are dropped out from the queue.

Let us consider two independent traffic flows with arrival rates of λ_1 and λ_2 for high and low priority, respectively. Although we have four priority ACs, the channel is preempted only at a given time between two ACs. For simplicity, we assume that the low-priority packets cannot be served when there is a high-priority traffic in-service. Moreover, the high-priority packets can preempt the low-priority ones if there are no resources available to them. Hence, we have two cases.

- **Case 1:** High-priority M/D/1/K queuing system (no low-priority packets in the queue)
- **Case 2:** Low-priority packets are being preempted by high-priority ones.

4.2.1 Case 1: Mean queuing delay for high-priority traffic

When there are no low-priority packets in the queue, it is assumed that the high-priority packets serve on a first come first serve basis and the queuing system is M/D/1/K. Thus, using the stochastic balance equation, we can obtain the steady-state probability that is the process is in n state as:

$$P_n = \rho^n P_0 \text{ ; where } n = 0, 1, 2, 3, \dots\dots, k \text{ and } \rho = \frac{\lambda}{\mu}$$

$$= (\lambda\, E[X])^n P_0 = \left(\frac{\lambda}{\mu}\right)^n P_0 \text{ where } E[x] = \frac{1}{\mu} \tag{7}$$

Hence, the mean waiting time for the high-priority packet (waiting in the queue) can be written as follows:

$$E[W_H] = \frac{\rho\,(1 + C_x^2) E[x]}{2(1-\rho)} \tag{8}$$

Where $C_x^2 = \frac{\sigma_x^2}{(E[x])^2} = 0$ as service time is fixed. Therefore (8) becomes:

$$E[W_H] = \frac{\rho\, E[x]}{2(1-\rho)} = \frac{\rho}{2\mu(1-\rho)} \tag{9}$$

4.2.2 Case 2: Mean queueing delay for low-priority traffic

Let us consider that the low-priority packet is in-service. Upon the arrival of high-priority traffic, the low-priory traffic will be preempted (blocked) until the high-priority packets are successfully transmitted. Once the service is available then the low-priority packets can resume transmissions. Thus, the service completion time for the low-priority packet is longer which is a combination of service completion time plus the additional delay due to the arrival of high-priority packets during the transmission. This can be formulated again using the M/D/1/K model. Hence, we can write, the mean waiting time for the low-priority packet with preemption as follows.

$$E[W_L] = \frac{\rho_L\, E[x]}{2(1-\rho_L)} = \frac{\rho_L}{2\mu(1-\rho_L)} + \frac{\rho}{2\mu(1-\rho)} \tag{10}$$

Equation (9) shows the mean packet queuing delay for PAC-MP-EDCA life-saving emergency traffic which is correlated with the results presented in Section 5.3. The Preemptive admission control (PAC) algorithm is discussed next.

4.3 The PAC Algorithm

In PAC-MP-EDCA, a wireless station first specifies its traffic characteristics and QoS needs using the traffic specification (T_{SPEC}). A new emergency traffic stream (node with traffic flow) can only join the network if either the network resources are available to serve the node or a node with high priority emergency traffic with existing ongoing nodes. The PAC algorithm is implemented in each of the wireless nodes at the MAC layer [35]. The pseudo-code of the proposed PAC-MP-EDCA Algorithm is presented next (Algorithm 1). We use L, H, P, and E for Life, Health, Property, and Environment, respectively. Moreover, the traffic flows T_{flows} is a positive integer represented by Z.

Algorithm 1 Proposed PAC-MP-EDCA Algorithm

```
Input:
    (i) Traffic priority list, $T_p \in$ [L, H, P, E];
    (ii) Required Timeslots, $T_{sl}$
    (iii) Traffic flows, $T_{flows} \in Z$;
Output:
    (i) Accept or Reject;
    (ii) Slot allocated;
Begin
for every $T_{flow}(i)$ do
    determine $T_P(i)$
    determine $T_{req}$
    determine $T_{free}$
    if $T_{req} \leq T_{free}$ then
        Accept
    Allocate timeslots
    else
        if $T_{req} > T_{free}$ & $T_P(i) > T_P(E)$ then
            Release timeslots occupied by Environment Node
            update $T_{free}$
            if $T_{req} > T_{free}$ & $T_P(i) > T_P(P)$ then
                Release timeslots occupied by Property Node
                update $T_{free}$
                if $T_{req} > T_{free}$ & $T_P(i) > T_P(H)$ then
                    Release timeslots occupied by Health Node
                    update $T_{free}$
                    Reject
                end if
            end if
        end if
    else
        Reject
    end if
end for
End
```

Suppose, there are S - 1 ongoing traffic streams. When the new emergency traffic stream Sth arrives, the PAC determines the available resources. If there are enough resources available to admit new emergency traffic stream Sth and satisfy QoS required by the new traffic stream without affecting the QoS required by the ongoing traffic stream. The admission is then granted to new traffic streams. Otherwise, the priority of the new traffic stream is checked. The system performance evaluation and results are discussed next.

5 Performance Evaluation and Results

5.1. Simulation environment

To study the performance of the proposed PAC-MP-EDCA and to compare it with MP-EDCA [8], and the standard EDCA [5], we develop simulation models using Riverbed Modeler version 18.0 [27]. The Riverbed Modeler simulation software was chosen due to its popularity and credibility [29]. Being a commercial simulation package, Riverbed Modeler offers a good development environment with various in-built tools to develop wireless MAC protocols under study, including IEEE standard 802.11e/EDCA, MP-EDCA, and the proposed PAC-MP-EDCA.

5.2 Modelling the network

The main objective of designing PAC-MP-EDCA is to provide a strict QoS guarantee to life-saving emergency traffic under high-traffic loads. Figure 4 shows a Riverbed representation of a fully connected network scenario with 60 emergency nodes of Risk to Life (RtoL) for simulating MP-EDCA-PAC. Each scenario uses voice traffic which is generated by an ‘Application Definition’ in the Riverbed Modeler simulator. The application starting time, duration, and the number of repetitions is configured in the ‘Profile Definition’. Both Application and Profile icons are placed on the top middle of Figure 4.

For performance evaluation purposes, we develop about 45 network Scenarios (15 Scenarios for each EDCA, MP-EDCA, and PAC-MP-EDCA). In each Scenario, we vary nodes from 4 to 60 to observe the system performance under low-to-high traffic loads. Each node communicates with the central node called an access point (AP) as an AP is configured to act as a central node. All other nodes communicate with the central node.

We consider uniform node distribution in simulating MP-EDCA and PAC-MP-EDCA where each network scenario consists of an equal number of emergency nodes (identical configuration). We increase the number of nodes up to 60 to observe the effect of system performance for various emergency priorities. In EDCA [47], all nodes use default SIFS and SlotTime as IEEE 802.11e/EDCA does not support any emergency traffics.

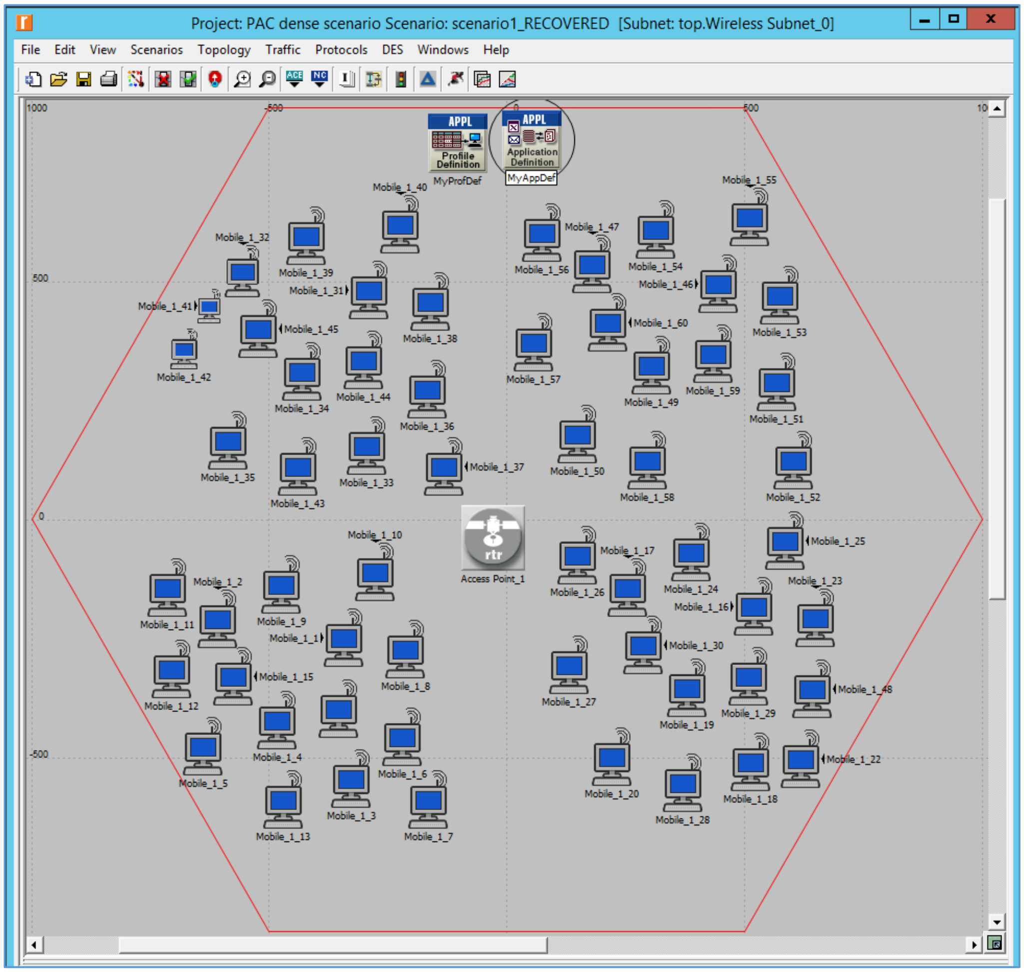


Figure 4: Riverbed representation of a fully connected network scenario of Risk to Life (RtoL) for simulating MP-EDCA-PAC (total 60 nodes).

Table 3 shows the parameters used in the simulation of PAC-MP-EDCA. Each simulation run lasted for 300 seconds. Real-time voice traffic is used to evaluate the system performance. The simulation models were developed using Riverbed Modeler to study the performance of PAC-MP-EDCA, MP-EDCA, and EDCA. The proposed scheme may be used for ad hoc (single hop) and EDCA based infrastructure networks (Table 3).

Table 3: Parameters used in the simulation.

<table>
<tr><td rowspan="1">General Parameter</td><td colspan="4">Data rate = 65Mbps (base)/600 Mbps (max)
Protocol = IEEE 802.11n
Number of MP-EDCA nodes: 4 to 60
Number of PAC-MP-EDCA nodes: 4 to 60
Application: Interactive voice (G.723.1.5.3K Encoder Scheme)
TXOP limit = 3 ms
Radio propagation: Free space model with 2.4 GHz frequency
Network area: 100 meters
Simulation time: 300 seconds</td></tr>
<tr><td rowspan="6">Contention Parameter</td><td colspan="4">PAC-MP-EDCA and MP-EDCA (Chosen values)</td></tr>
<tr><td>Risk to Life (RtoL) Priority Nodes</td><td>Risk to Health (RtoH) Priority Nodes</td><td>Risk to Property (RtoP) Priority Nodes</td><td>Risk to Environment (RtoE) Priority Nodes</td></tr>
<tr><td>RtoLSIFS = 10 µs
RtoLSlotTime =25 µs
AIFS [0] = 1 slot
WMin [0] = 2 slots
WMax [8] = 8 slots</td><td>RtoHSIFS = 25 µs
RtoHSlotTime =40 µs
AIFS [0] = 1 slot
WMin[0] = 2 slots
WMax[8] = 8 slots</td><td>RtoPSIFS = 40 µs
RtoSIFS = 55
AIFS [0] = 1 slot
WMin [0] = 2 slots
WMax [8] = 8 slots</td><td>RtoPSIFS = 55 µs
RtoESlotTime = 70 µs
AIFS [0] = 1 slot
WMin [0] = 2 slots
WMax [8] = 8 slots</td></tr>
<tr><td colspan="4">EDCA (802.11e)</td></tr>
<tr><td colspan="2">Default values</td><td colspan="2">Chosen values</td></tr>
<tr><td colspan="2">SIFS = 10 µs
Slot Time = 20 µs
AIFS [0] = 2 slots</td><td colspan="2">WMin [0] = 2 slots
WMax [8] = 8 slots</td></tr>
</table>

5.3 Results and Discussion

We compare the performance of our proposed PAC-MP-EDCA with MP-EDCA [8] and the standard EDCA [5]. For system performance evaluation, we consider three important commonly used network performance metrics, such as MAC delay; Packet retransmission attempt; and Throughput.

The MAC delay (network-wide as well as an individual node) is one of the key performance metrics that we consider in this research. The MAC delay is measured from the moment an application frame is queued at the MAC layer until the frame is successfully transmitted. This includes queuing delay, channel contention, and frame transmission time. The queuing delay of PAC-MP-EDCA is analyzed in Section 4.2.1. Moreover, other QoS parameters such as throughput, and packet retransmission attempts are also used to study the effectiveness of the proposed PAC-MP-EDCA protocol.

5.3.1 Queuing delay

In Fig. 5, we plot mean queue delays versus the number of life-saving emergency nodes for PAC-MP-EDCA. We study the system queuing delay characteristics and validate our analytical model developed in Equation (9) using MATLAB-based numerical studies. We observe that both analytical and simulation queuing delays of PAC-MP-EDCA remain the same for emergency nodes up to 12. When the number of life-saving emergency nodes increases from 12 to 60, the analytical queuing delays (solid line) are slightly lower (up to 8%) than the simulation ones, but these differences are not very significant. A close match of analytical and simulation results validates our queue delay model for PAC-MP-EDCA life-saving emergency nodes. We consider Fig 5 to validate the simulation results such as MAC delay, packet retransmission attempts, and throughput presented next.

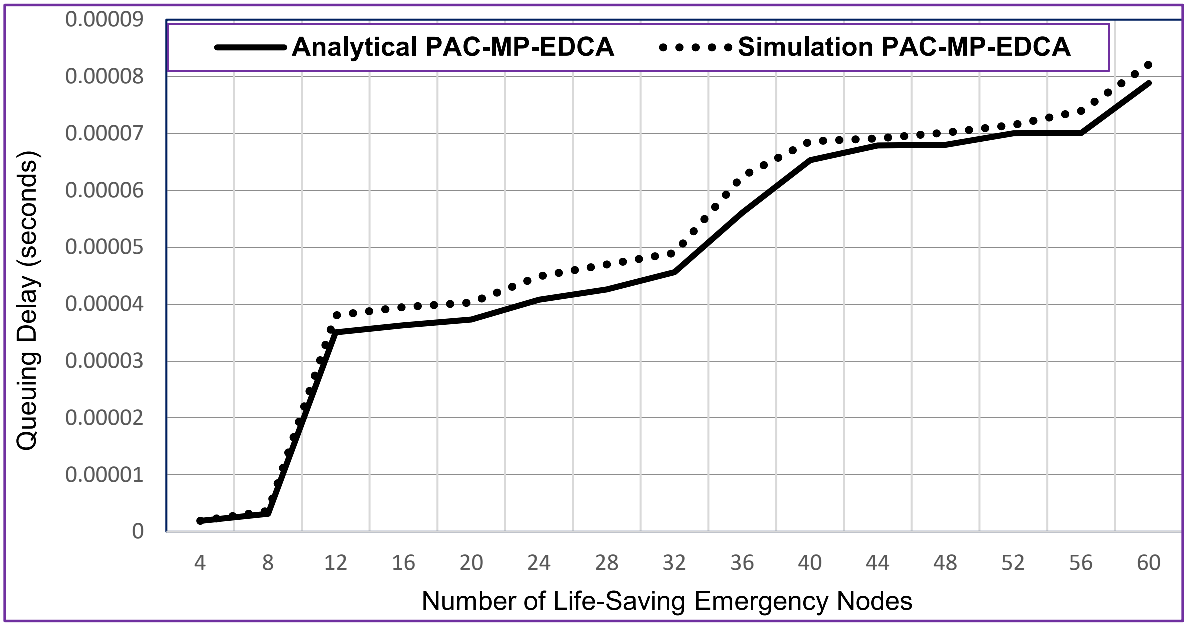


Figure 5: PAC-MP-EDCA queue delay versus the number of life-saving emergency nodes.

5.3.2 Network-wide MAC Delay

In Fig. 6, we plot network mean packet delays versus the number of life-saving emergency nodes for PAC-MP-EDCA. The results for the standard EDCA and MP-EDCA are also shown for comparison purposes. The MAC delays remain the same and very low for all three protocols for emergency nodes up to 25. When the number of life-saving emergency nodes increases from 25 to 60, the network-wide MAC delays for EDCA sharply increase while it remains low for both MP-EDCA and PAC-MP-EDCA. For instance, the network MAC delay of EDCA is about 0.067 sec for N = 60 life-saving emergency nodes. This increased MAC delay for EDCA is due to the high packet collisions as a result of high contention among the nodes.

Let us focus on the packet delay performance of PAC-MP-EDCA under high-traffic loads. By looking at Fig. 7 (an enlarged version of Fig. 6), one can observe that PAC-MP-EDCA achieves lower packet delays than MP-EDCA especially for a network with more than 50 life-saving emergency nodes. For instance, PAC-MP-EDCA achieves about 90% lower mean delays (network-wide) than MP-EDCA for a network with N= 60 nodes. The low packet delays are achieved due to the preemptive admission control (PAC) properties of PAC-MP-EDCA in which the effectiveness of the PAC mechanism is remarkable for an increased number of life-saving emergency nodes (from 45 onwards) where the network-wide delays are not affected by the increased network loads. Thus, based on the simulation results, one can confirm that the proposed PAC-MP-EDCA mechanism can be an excellent candidate to support life-saving emergency traffics in WLANs during an emergency period in which a large number of users demand emergency channel access for communications.

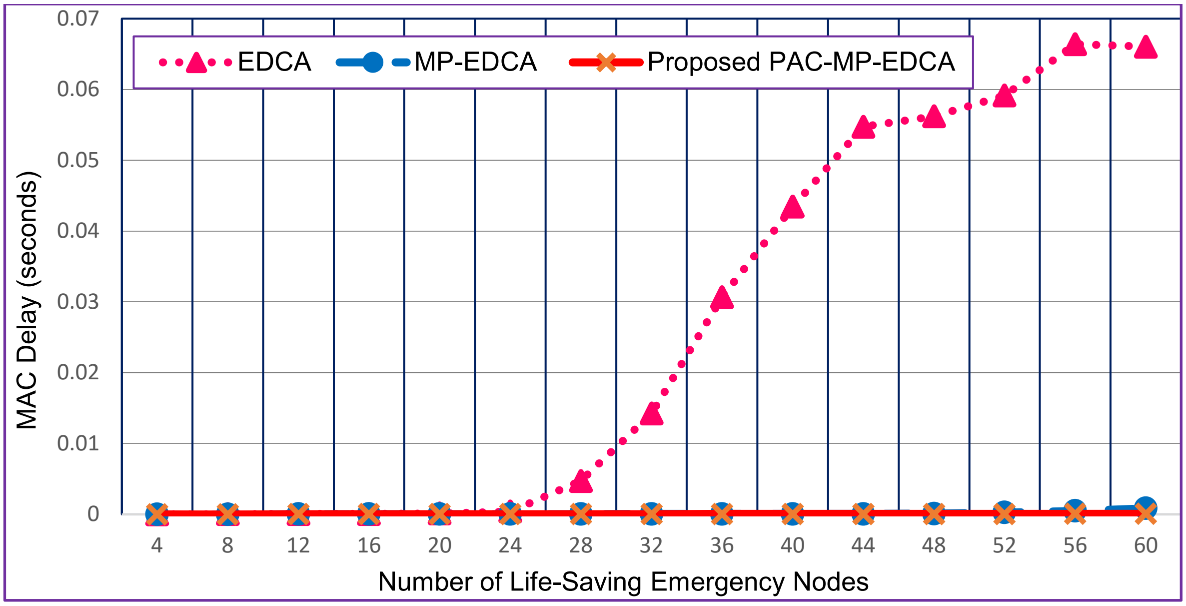


Figure 6: Network-wide MAC delays of PAC-MP-EDCA, MP-EDCA, and EDCA.

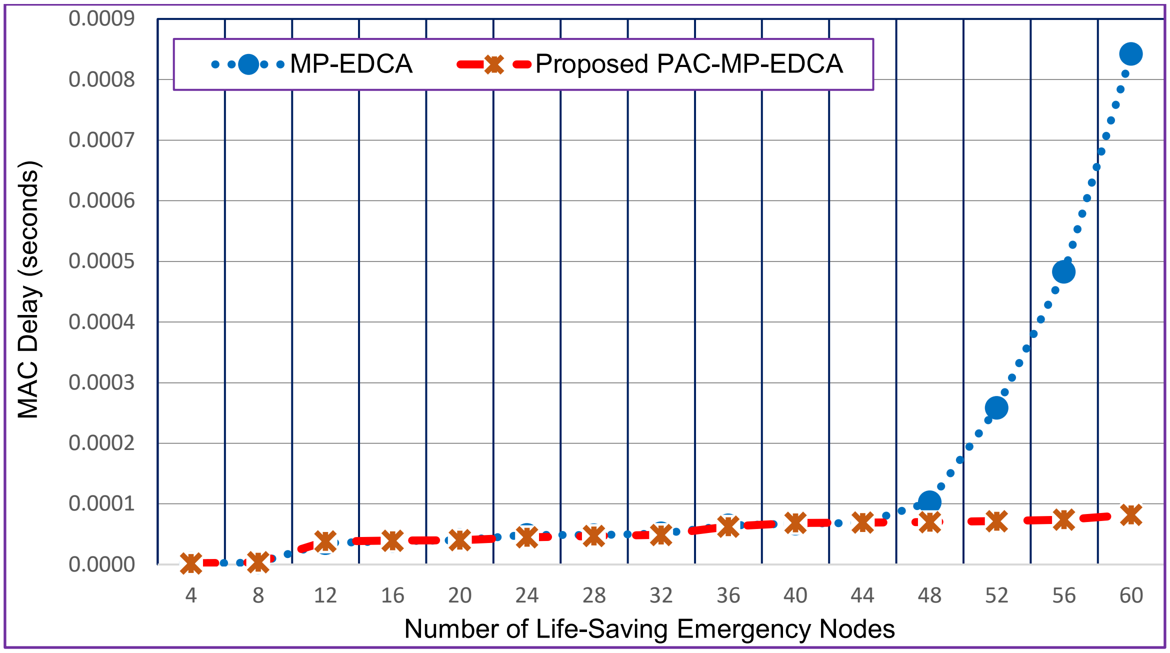


Figure 7: This diagram is redrawn by expanding Fig. 6 for a clear illustration of network MAC delays of PAC-MP-EDCA and MP-EDCA.

5.3.3 Individual Node MAC Delay

In Fig. 8, we plot individual node mean packet delays against the number of life-saving emergency nodes of PAC-MP-EDCA. The results for the standard EDCA and MP-EDCA are also shown for comparison. Figure 9 is a zoomed view of Fig. 8 for a clear illustration of MAC delays of PAC-MP-EDCA and MP-EDCA. With an increasing number of life-saving emergency nodes from 40 to 60, where PAC-MP-EDCA delays remain low and constant compared to MP-EDCA delays which increase from 0.1 ms at node 40 to 1.1ms at node 60.

By looking at Fig. 9, we observe that the mean packet delays of a life-saving emergency node for PAC-MP-EDCA are much lower than MP-EDCA. For instance, the mean packet delays of a life-saving emergency node for MP-EDCA and PAC-MP-EDCA are about 1095μs and 26.3μs, respectively at N = 60 node (high-traffic scenario). A life-saving emergency node in PAC-MP-EDCA achieves about 98% lower MAC delays than MP-EDCA.

Generally, PAC-MP-EDCA offers very low and constant node delays regardless of the increasing of life-saving emergency nodes in the network indicating that the proposed system can provide a QoS guarantee (in terms of packet delays) to life-saving emergency traffics in highly loaded networks.

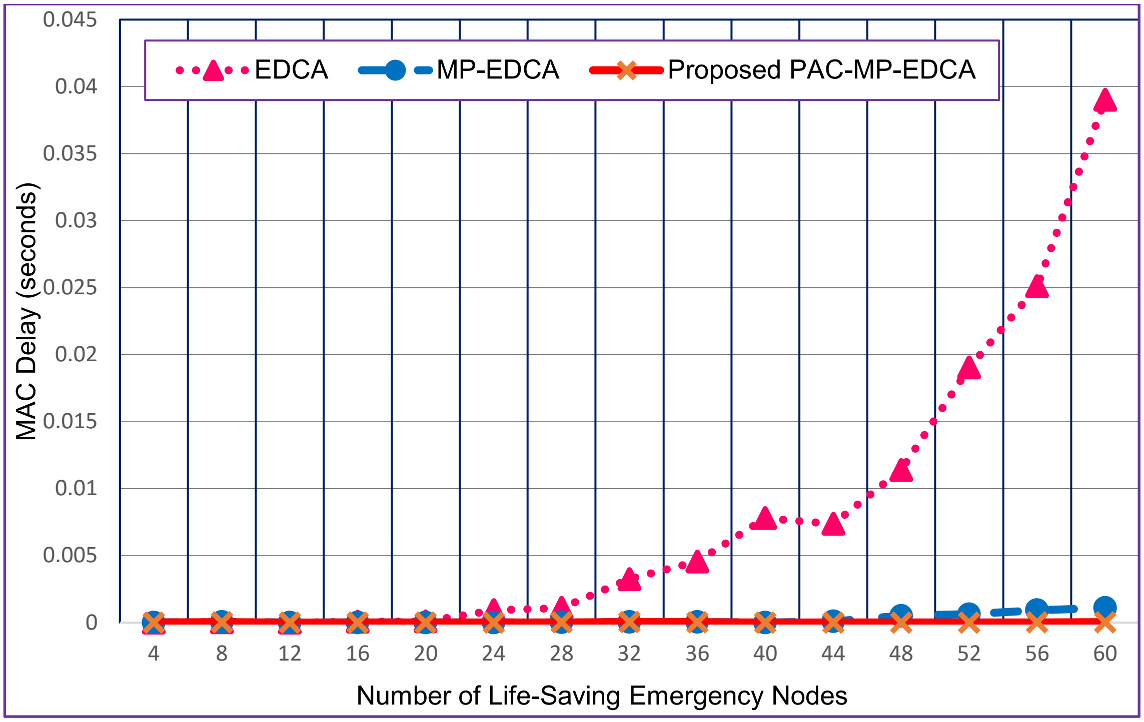


Figure 8: Node MAC delays of EDCA, MP-EDCA, and the proposed PAC-MP-EDCA.

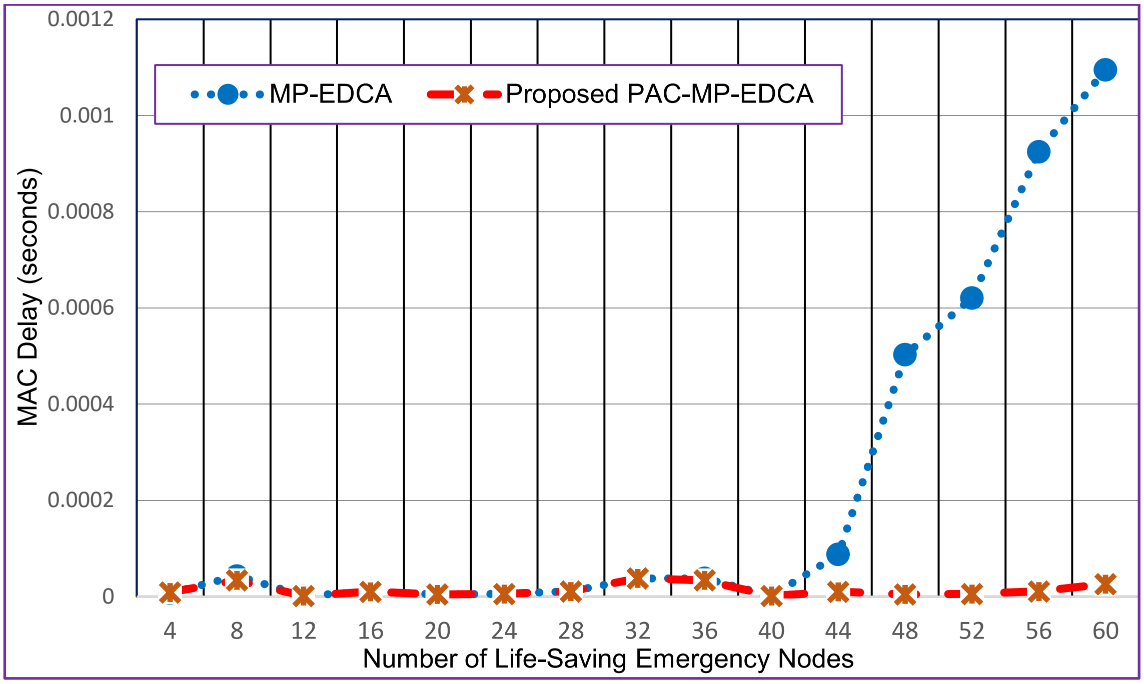


Figure 9: This diagram is redrawn by expanding Fig. 7 for a clear illustration of node MAC delays of PAC-MP-EDCA and MP-EDCA life-saving emergency nodes.

5.3.4 Packet retransmission

Packet retransmission is a commonly used approach to recover packet errors and losses [31]. In Fig. 10, we plot the number of retransmitted packets against the number of life-saving emergency nodes. We compare the performance of the proposed PAC-MP-EDCA with MP-EDCA and the standard 802.11e (EDCA). One can observe that PAC-MP-EDCA improves the efficiency of MAC-layer retransmissions by reducing the number of retransmissions required to recover the losses. If we look closely at Fig. 10, one can observe that the number of retransmitted packets increases with the increase in the number of life-saving emergency nodes, especially for EDCA and MP-EDCA. The proposed PAC-MP-EDCA achieved about 92% and 79% lower re-transmitted packets over the standard EDCA and MP-EDCA, respectively at N= 60 node. Therefore, the PAC algorithm can be applied to WLANs to achieve efficient retransmission.

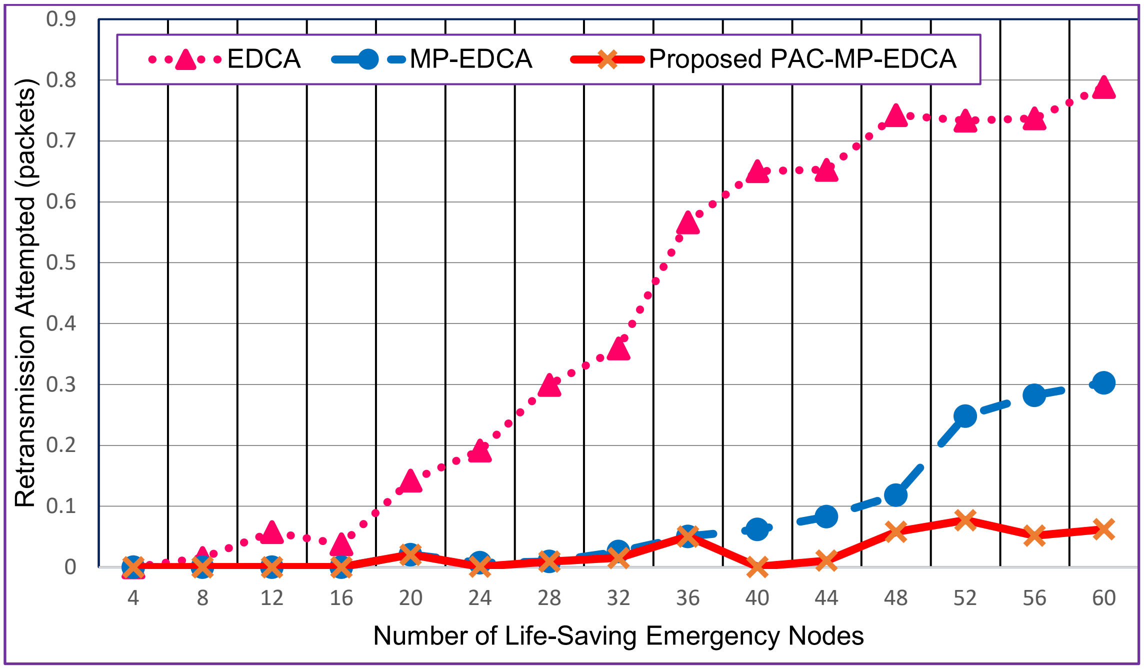


Figure 10: Packets retransmission attempts. Comparison of EDCA, MP-EDCA, and the proposed PAC-MP-EDCA.

5.3.5 Average throughput

Figure 11 exhibits the mean throughput for a variable number of life-saving emergency nodes. We observe that the proposed PAC-MP-EDCA offers an improved user throughput of 9 Mbps while the lowest value is attributed to the standard EDCA that provides up to 7 Mbps for 60 nodes. Generally, all three protocols provide equal throughput for a low number of nodes (up to 25 nodes).

This is because with fewer nodes there is no network congestion. The main contribution of the proposed PAC protocol is remarkable for the increased number of nodes where traffic generated by life-saving nodes is prioritized. PAC achieved up to 23% and 15% higher throughput over the standard EDCA and MP-EDCA protocols, respectively. It is worth noting that the key difference between these protocols is noticed for an increased number of nodes. Thus, the proposed PAC is needed for improving the user throughput for prioritized traffic in real-world applications.

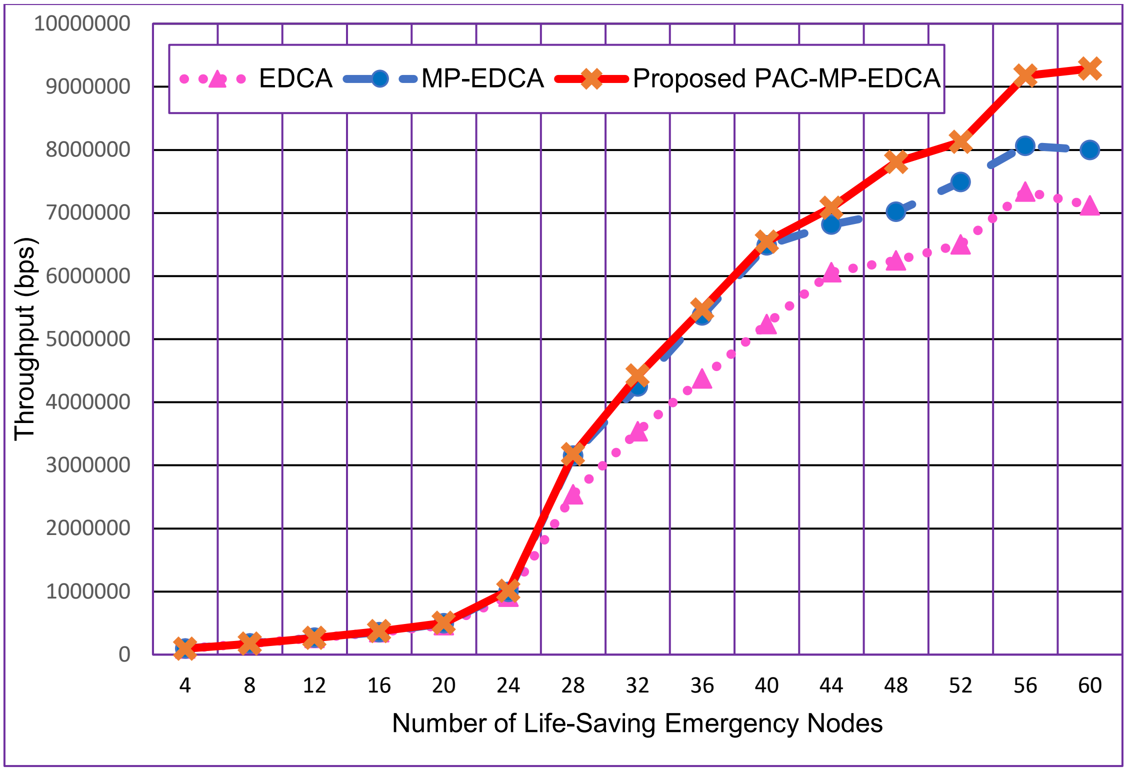


Figure 11: Mean throughput performance. Comparison of EDCA, MP-EDCA, and the proposed PAC-MP-EDCA.

5.3.6 Simulation results validation

Although Riverbed Modeler is one of the credible simulation tools, it may produce invalid results if the simulation parameters are incorrectly configured. To validate the results, we have used two validation techniques discussed in [32]. First, we use the concept of face validation, which is when the model's behavior is expected and reasonable. Second, we compare our results with the MP-EDCA [8] and the standard IEEE 802.11e EDCA [33]. We also check simulation log files to ensure that there were no errors and the simulation scenarios run smoothly. In addition, a close matching of analytical and simulation results (Fig.5) of PAC-MP-EDCA delays validates the remaining simulation results.

5.3.7 Implementation aspects of PAC-MP-EDCA

In any disaster situation, the first responders (relief workers) protect human life, save property, and protect the environment. In doing so, the first responders need reliable communication during an emergency to save human lives. Also, the first responders need resources that are with the central coordinator node as shown in Fig. 3. The network performance degrades significantly when a high number of users (first responders) might have life-saving emergency traffics and would want to communicate with a central coordinator node for resources.

In implementing the PAC-MP-EDCA algorithm at the central coordinator node, the network performance issues can be addressed effectively. In case of a dense emergency, such as a disaster, PAC-MP-EDCA can be dynamically activated at the central coordinator node to admit life-saving emergency (i.e. Risk to life) nodes based on the available network capacity. Moreover, all the nodes with Risk to life priority can preempt the low priority emergency traffic owing to the inherent MP-EDCA support. When planning for deployment of WLANs, system planners can consider PAC-MP-EDCA to support emergency communication where life-saving emergency traffics has the highest channel access priority. PAC-MP-EDCA is most useful in scenarios where there is at least one node that can act as a central coordinator node for admission control.

6 Conclusions

In this paper, we proposed a preemptive admission control (PAC-MP-EDCA) mechanism for providing a strict QoS guarantee to life-saving emergency traffic in a saturated emergency where a high number of users report an emergency. The proposed method is based on capacity analysis of emergency traffic. The maximum number of high-priority traffic flows is determined by the system capacity analysis. We developed an M/D/1/K queuing model to derive mean delays for high-priority emergency traffic and to estimate/validate system performance. The performance of PAC-MP-EDCA is evaluated by measuring mean throughput, end-to-end delay, and packet retransmission attempts using the Riverbed Modeler simulator. The simulation results obtained have shown that the proposed PAC-MP-EDCA achieved up to 98% lower mean MAC delays for life-saving emergency node, 79% lower packet retransmitted, and 15% higher throughput than MP-EDCA protocol, especially under high traffic loads. In comparison with the IEEE 802.11e EDCA standard, the proposed PAC-MP-EDCA provides a significant performance improvement. Therefore, PAC-MP-EDCA assures a strict QoS guarantee to life-saving emergency traffic in high network loading scenarios. However, nodes with risk to life-saving emergency traffic will not be admitted if the network cannot support upcoming life-saving traffics. This admission control system guarantees a strict QoS to life-saving emergency traffic in operation. The findings reported in this paper provide some insights into the admission control approach in achieving a QoS guarantee for emergency traffic that can help network researchers and engineers to contribute further towards developing the next-generation wireless networks. However, redesigning frame aggregation with a simple block acknowledgment to extend PAC-MP-EDCA is suggested as future work.

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