A Multi-Priority Service Differentiated and Adaptive Backoff Mechanism over IEEE 802.11 DCF for Wireless Mobile Networks

Bo Zheng[1], Hengyang Zhang[1], Kun Zhuo[2] and Huaxin Wu[3]
[1] Information and Navigation Institute, Air Force Engineering University
Xi'an 710077 - China
[e-mail: zbkgd, hareed@163.com]
[2] PLA Unit of 93995
Xi'an 710306 - China
[e-mail: zhuokun_TG@163.com]
[3] Huangpi NCO School, Air Force Early Warning Academy
Wuhan 430019 - China
[e-mail: wnewhua@qq.com]
*Corresponding author: Bo Zheng

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Abstract

Backoff mechanism serves as one of the key technologies in the MAC-layer of wireless mobile networks. The traditional Binary Exponential Backoff (BEB) mechanism in IEEE 802.11 Distributed Coordination Function (DCF) and other existing backoff mechanisms poses several performance issues. For instance, the Contention Window (CW) oscillations occur frequently; a low delay QoS guarantee cannot be provided for real-time transmission, and services with different priorities are not differentiated. For these problems, we present a novel Multi-Priority service differentiated and Adaptive Backoff (MPAB) algorithm over IEEE 802.11 DCF for wireless mobile networks in this paper. In this algorithm, the backoff stage is chosen adaptively according to the channel status and traffic priority, and the forwarding and receding transition probability between the adjacent backoff stages for different priority traffic can be controlled and adjusted for demands at any time. We further employ the 2-dimensional Markov chain model to analyze the algorithm, and derive the analytical expressions of the saturation throughput and average medium access delay. Both the accuracy of the expressions and the algorithm performance are verified through simulations. The results show that the performance of the MPAB algorithm can offer a higher throughput and lower delay than the BEB algorithm.

Keywords: Wireless mobile network, backoff algorithm, real-time transmission, multi-priority, Markov chain

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1. Introduction

With the tremendous development and rapid growing application, wireless mobile networks, such as Mobile Ad hoc Networks (MANET) and Wireless Sensor Networks (WSN), have gained popularity at an unprecedented rate over the last decade. Concurrent with the expansion is a high demand for multi-priority traffic transmissions with differentiated services, including both real-time and non-real-time applications. The real-time applications, such as the conversational audio and video conferences, on-demand multimedia services, and emergency traffic, require stringent Quality of Service (QoS) guarantees. Nevertheless, the best effort applications, such as file transfer, are more tolerant to changes in bandwidth and delay, and generally have backlogged packets for transmission. Due to the shared nature of the underlying wireless channel, it is a challenging task for wireless mobile networks to support multiple types of traffic and provide differentiated services. Support from the Media Access Control (MAC) layer to regulate access to the wireless channel is required for providing QoS support. Therefore, it is necessary to tailor the MAC protocol to provide differentiated services for various data flows according to their priorities.

Nowadays the MAC protocols employed by wireless mobile networks are mainly divided into two categories: the scheduling-based MAC protocols, like Time Division Multiple Access (TDMA) [1]-[3], and the contention-based MAC protocols [4][5], such as, ALOHA, Carrier Sense Multiple Access (CSMA) and IEEE 802.15.4. In this paper, we focus on the most widely used one, the IEEE 802.11 protocol, which belongs to the latter category.

In the contention-based MAC protocols, backoff algorithm is the direct issue influencing on throughput and transmission delay. How to tailor the backoff algorithm to avoid collisions and support multi-priority service differentiation has gained much attention. The traditional IEEE 802.11 Distributed Coordination Function (DCF) protocol adopts the Binary Exponential Backoff (BEB) mechanism, which cannot differentiate multi-priority services [6]. Moreover, it poses several performance issues, such as the Contention Window (CW) oscillations [7][8]. In order to achieve the co-transmission of multi-priority data flows in wireless networks, IEEE 802.11 Task Group E has proposed the Enhanced Distributed Channel Access (EDCA) mechanism to provide service differentiation [9]. The EDCA mechanism provides different QoS guarantees to different priority traffic by independent priority parameters in the backoff mechanism. But it has weak self-adaptation to the varying traffic and can only support limited traffic types [10]-[13]. Therefore, we are motivated to propose a backoff mechanism with low transmission delays, large network capacity, high flexibility and scalability, and multi-priority service differentiation for the contention-based MAC protocols. The mechanism should provide an instant access to the channel with the lowest delay for the highest priority traffic and a fair opportunity to access for the same priority traffic, thus improve the network performance efficiently.

Based on the above observations, in this paper we introduce a novel Multi-Priority service differentiated and Adaptive Backoff (MPAB) mechanism to provide an efficient and fair backoff solution for wireless mobile networks. The proposed mechanism has the following attractive advantages:

(1) *The proposed algorithm supports any number of traffic priority types.* Different traffic types are differentiated by the forwarding and receding transition probabilities of the adjacent backoff stages according to their priorities in the MPAB algorithm. Furthermore, we adopt a

discrete 2-dimensional Markov chain model to analyze the MPAB algorithm performance, and show its performance advantage over the Binary Exponential Backoff (BEB) algorithm through extensive simulations.

(2) *The transition probabilities of backoff stages in the proposed algorithm are real-time controllable according to the QoS requirement of traffic.* In the MPAB algorithm, the transition probabilities are derived from the QoS requirement of traffic, and thereby can be controlled and updated in order to meet the variations of traffic categories in the network. In addition, we restrict the transitions of backoff stages only between the adjacent stages, which can effectively avoid the decline of network performance caused by the Contention Window (CW) oscillations.

(3) *The proposed algorithm uses a channel collision flag to show whether a collision happens as a hint to choose a proper backoff stage.* Considering the simplicity and feasibility of the algorithm, we define the channel collision flag. As a result, the MPAB algorithm enables nodes to adapt to different congestion levels by choosing the next backoff stage with reference to the collision event happened in the channel.

The remainder of the paper is organized as follows: Section 2 briefly describes the review of some related work. In Section 3, we propose the MPAB algorithm. Section 4 and 5 presents the analysis of saturation throughput and medium access delay in the MPAB algorithm, respectively. Section 6 shows the simulation results and analytic results. Finally, we conclude the paper in Section 7.

2. Related Work

Over the past decades, wireless networks with IEEE 802.11 DCF [6] have been widely implemented for its low cost and simple deployment. However, it can only support the best effort traffic. The backoff mechanism it adopts is the BEB algorithm, which is also widely used in the contention-based MAC protocols for wireless networks, such as IEEE 802.15.4, CSMA, MACA (Multiple Access Collision Avoidance) and FAMA (Floor Acquisition Multiple Access). In the BEB algorithm, the CW size decreases to the minimum whenever the data is transmitted successfully, and is doubled whenever a collision occurs. The deficiencies of the algorithm have been investigated in [7] and [8]. (1) The dependency of the successive traffic flows is not considered. When the packet collision probability is large, the CW needs to be enlarged several times to send the packet. However, once the packet is transmitted successfully, the CW is reset to the minimum. This is the CW oscillation phenomenon, and it occurs repeatedly. (2) When the CW increases, the value of the adjusting factor is 2 invariably, and when the network load changes, the network cannot converge rapidly to the optimum backoff state. (3) Different priority traffic cannot be differentiated, and QoS guarantee cannot be provided for delay sensitive traffic.

Recent years, for some practical networks, many backoff schemes have been proposed against the deficiencies in the BEB algorithm. MILD (Multiple Increase Linear Decrease) [14] and EIED (Exponential Increase Exponential Decrease) [15] are improved efforts on the BEB algorithm against the renewal rule of the CW. Although network performance is improved on some degree, both algorithms have some limitations in application. MILD is not suitable for high traffic load, since it can increase collision probability and decrease the network throughput, while EIED may suffer unfair channel access when the number of nodes is small. Furthermore, they are both applicable for single traffic type. Ye and Tseng, in [16], proposed a Multichain Backoff (MCB) algorithm, in which several backoff chains were generated through reorganizing the backoff states in the BEB algorithm, and several backoff states were contained in every backoff chain again. The algorithm can accommodate to different degrees of network congestion. However, it cannot differentiate the traffic priority, and is too complex to implement. He, et al, in [17], proposed a Reservation based Backoff (ReB) to achieve resource reservation by using one or multiple time slots for video streaming borrowed from R-ALOHA. The method can be adopted for video streaming transmissions in wireless mobile networks, but it cannot differentiate the traffic priority either.

In order to meet the requirement of multi-priority service differentiation in packet transmissions in WLAN, the IEEE 802.11 working group has issued the EDCA mechanism to support applications with QoS requirement containing different priorities [9]. It assigns the minimum CW size (CW_{min}), maximum CW size (CW_{max}), arbitration inter-frame space ($AIFS$) and the limit of consecutive transmission opportunity ($TXOP$) with different values to achieve service differentiation among four Access Categories (ACs), i.e., AC_VO (for voice traffic), AC_VI (for video traffic), AC_BE (for best effort traffic) and AC_BK (for background traffic), as is shown in **Table 1**. One problem of the basic EDCA mode is that CW size and backoff function of each queue are static, and the dynamics of the wireless channel is not taken into account. Romdhani, et al, in [18], proposed an Adaptive EDCF (AEDCF) scheme, where relative priorities were provided by adjusting the CW size of each traffic according to application requirements and network conditions. After each successful transmission, AEDCF does not reset the CW size. Hong, et al, in [19], proposed a backoff algorithm that enabled each node to dynamically adapt its CW according to channel status, and the algorithm can be extended to provide differentiated services according to traffic priority. Deng in [20] proposed a Priority Enforced Slow-start Backoff (PSSB) algorithm for multimedia transmissions, which employed a distributed adaptive CW control mechanism to mitigate intensive collisions in congested scenarios and support priority traffic. In addition, IEEE 802.15.4 standard in [21] and [22] also supports the multi-priority service differentiation through its backoff scheme, where the minimum and maximum values of CW is uniformly distributed over different intervals to differentiate the CW size according to different priorities. However, nodes rather than traffic are assigned with different priorities in the standard.

Table 1. Parameter setting of IEEE 802.11e EDCA protocol

Priority	Traffic type	AIFS	CW_{min}	CW_{max}	TXOP
0	Voice	2	7	15	0.003
1	Video	2	15	31	0.006
2	Best effort	3	31	1023	0
3	Background	7	31	1023	0

Performance evaluation of the proposed backoff schemes is also a major aspect of efforts made in this field. G. Bianchi in [7] firstly introduced a discrete-time 2-dimensional Markov chain to compute the saturation throughput performance of IEEE 802.11 DCF under ideal channel conditions. However, Bianchi’s model does not consider the backoff suspension and finite retry limit. Afterwards, this mathematical model, as a common method, has been adopted by many researchers to analyze the performance of their improvements or investigations in [6], [20], and [23]-[27]. Wu, et al., in [24], improved Bianchi’s model with finite retry limit, but still ignoring the backoff suspension. Foh, et al., in [25], considered both of the issues simultaneously in their Markov chain model, and thereby introduced a mathematical model of the 3-dimensional Markov chain. Ye, et al., in [16] also utilized the

3-dimensional Markov chain to analyze the saturation throughput of the backoff mechanism they proposed. Chatzimisios, et al, in [28], extended the performance metrics from the throughput and average delay to the packet drop probability, the average time to drop a packet, and the packet interarrival time, also via the Markov chain model. In addition, some other analytical models were also employed. G. Bianchi in [29] derived the transmission probability τ based on elementary conditional probability arguments, and proposed an alternative derivation of the average delay via Little's Result. Zhao, et al., in [30], proposed the M/G/1/K and M/M/1/K queueing models to characterize the packet delay in nonsaturated conditions. Vardakas, et al., in [31] presented a novel analytical method to analyze the end-to-end delay containing the MAC delay and the queueing delay. Z-transform of backoff duration was used to obtain the mean value, variance and probability distribution of the MAC delay. For the queueing delay analysis, a M/G/1 queue and an ON-OFF model were employed respectively.

3. MPAB Algorithm

3.1 Algorithm Description

In MPAB algorithm, every node in the network maintains a diagram for the backoff stage transition, as shown in **Fig. 1**. The MPAB algorithm contains $m+1$ backoff stages, i.e., $0,1,\cdots,m$. We define the follow parameters in the algorithm:

- $CW_{\min}$: the minimum CW;
- $CW_{\max}$: the maximum CW;
- W_i $(0 \le i \le m)$: the CW size of the backoff stage i;
- k $(0 \le k \le K)$: the traffic priority, where $k=0$ represents the highest priority, and $k=K$ represents the lowest priority;
- $u_{i,k}$ $(0 \le i \le m-1, 0 \le k \le K)$: the transition probability from the backoff stage i to $i+1$, when the priority is k;
- $v_{i,k}$ $(0 \le i \le m-1, 0 \le k \le K)$: the transition probability from the backoff stage $i+1$ to i, when the priority is k;
- f_{col}: the channel collision flag to record whether a collision happens in the channel. If a collision occurs, $f_{col}=1$; if not, $f_{col}=0$.

Since the CW size of the latter backoff stage is 2 times of that in the former stage, it can be derived that $W_i = 2^i W_0 (0 \le i \le m)$. We can also easily acquire that $W_0 = CW_{\min}+1$ and $W_m = CW_{\max}+1$.

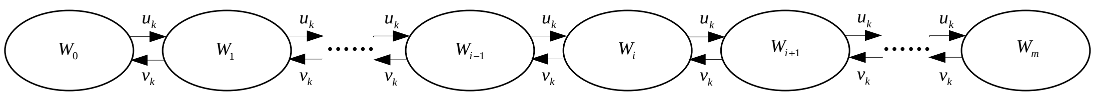


Fig. 1. Backoff stages in MPAB algorithm

In order to avoid the CW oscillations caused by the abrupt change of the node backoff stage, the MPAB algorithm controls that the backoff stages can only transit to the adjacent ones, as shown in **Fig. 1**. In the paper, we assume $u_{0,k} = u_{1,k} = \cdots = u_{m,k} = u_k$ and $v_{0,k} = v_{1,k} = \cdots = v_{m,k} = v_k$ for ease of study. In this case, the optimal value of u_k and v_k can be obtained in Section 6. In MPAB algorithm, since the network performance is determined by the values of u_k and v_k to a great extent, the multi-priority service differentiation is achieved by different values of u_k

and v_k . How to determine the values of u_k and v_k for a certain traffic priority will be shown in Section 6.3.

The MPAB algorithm operates as follows. When a node needs to send a packet, it randomly chooses a backoff value from its current CW. When the wireless channel is sensed idle for a DIFS period, the backoff process will be started. During the process, if the channel is sensed idle for a time slot, the backoff counter is decreased by 1, otherwise it is frozen until the channel is idle again. During backoff, the node also detects any collision caused by other nodes. f_{col} , described above, is used for this purpose. If the node itself experiences a collision or it detects the channel is busy for a period longer than the transmission time of the smallest frame but does not receive a frame successfully, the value of f_{col} is set to 1. The value is reset to 0 after each successful transmission. Once the backoff counter reaches 0, the node starts to send packet.

The backoff stage transition in MPAB algorithm is shown in **Fig. 2**. As can be seen in **Fig. 2**, after the backoff process, if the packet is sent unsuccessfully, the node backoff stage transits forward, i.e. the size of CW is doubled; if the packet is sent successfully, the next backoff stage is determined by the current values of f_{col} , u_k and v_k . Assuming that a node sends a packet at the backoff stage i ($0 \le i \le m$), if unsuccessfully and $i < m$, the node backoff stage will transit to the stage $i+1$; if unsuccessfully and $i = m$, the node backoff stage will not change; if successfully, the node backoff stage will transit to the stage $i+1$ with the probability $f_{col} \cdot u_k$, or transit to the stage $i-1$ with the probability $(1-f_{col}) \cdot v_k$, or stay at stage i with the probability $1 - f_{col} \cdot u_k - (1-f_{col}) \cdot v_k$. This can be interpreted intuitively that if a collision happens while the node is sending a packet, or a collision is sensed during the node backoff process, meaning that the channel is busy at present, the node backoff stage will transit forward or stay unchanged; if the packet is sent successfully, or a collision is not sensed during the node backoff process, meaning the channel is idle at present, the node backoff stage will transit backward or stay unchanged.

3.2 System Modeling

In this section, we will adopt the discrete 2-dimensional Markov chain to model the MPAB algorithm. As the former studies in this field, we assume the network operates in saturation conditions, i.e., the transmission queue of each node is assumed to stay nonempty. It is also assumed that, under such a condition, the collision probability of each transmission attempt is a constant and independent value p .

Let the number pair (i, j) represents the node backoff state, where i represents the current backoff stage. The size of the current CW is $W_i = 2^i W_0, i \in [0, m]$. j represents the current backoff value, $j \in [0, W_i - 1]$. Therefore, the node backoff state space is $\Omega = \{(i, j) | i \in [0, m], j \in [0, W_i - 1]\}$. Let $(s(t), b(t))$ represents the node backoff state at time t , and further define the one-step state transition probability $P\{i', j' | i, j\} = P\{s(t+1) = i', b(t+1) = j' | s(t) = i, b(t) = j\}$. So, the 2-dimensional stochastic process $(s(t), b(t))$ is the discrete 2-dimensional Markov chain with the state space Ω . $b_{i,j} = \lim_{t \to \infty} P\{s(t) = i, b(t) = j\}$ represents the steady state probability of every state in the Markov chain.

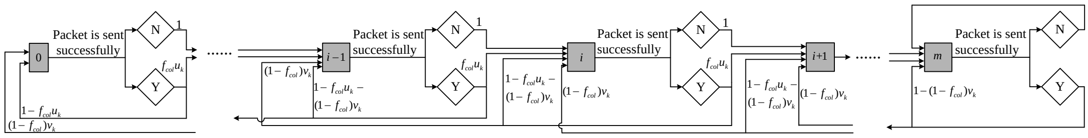


Fig. 2. Flow of the backoff stage transition in MPAB algorithm

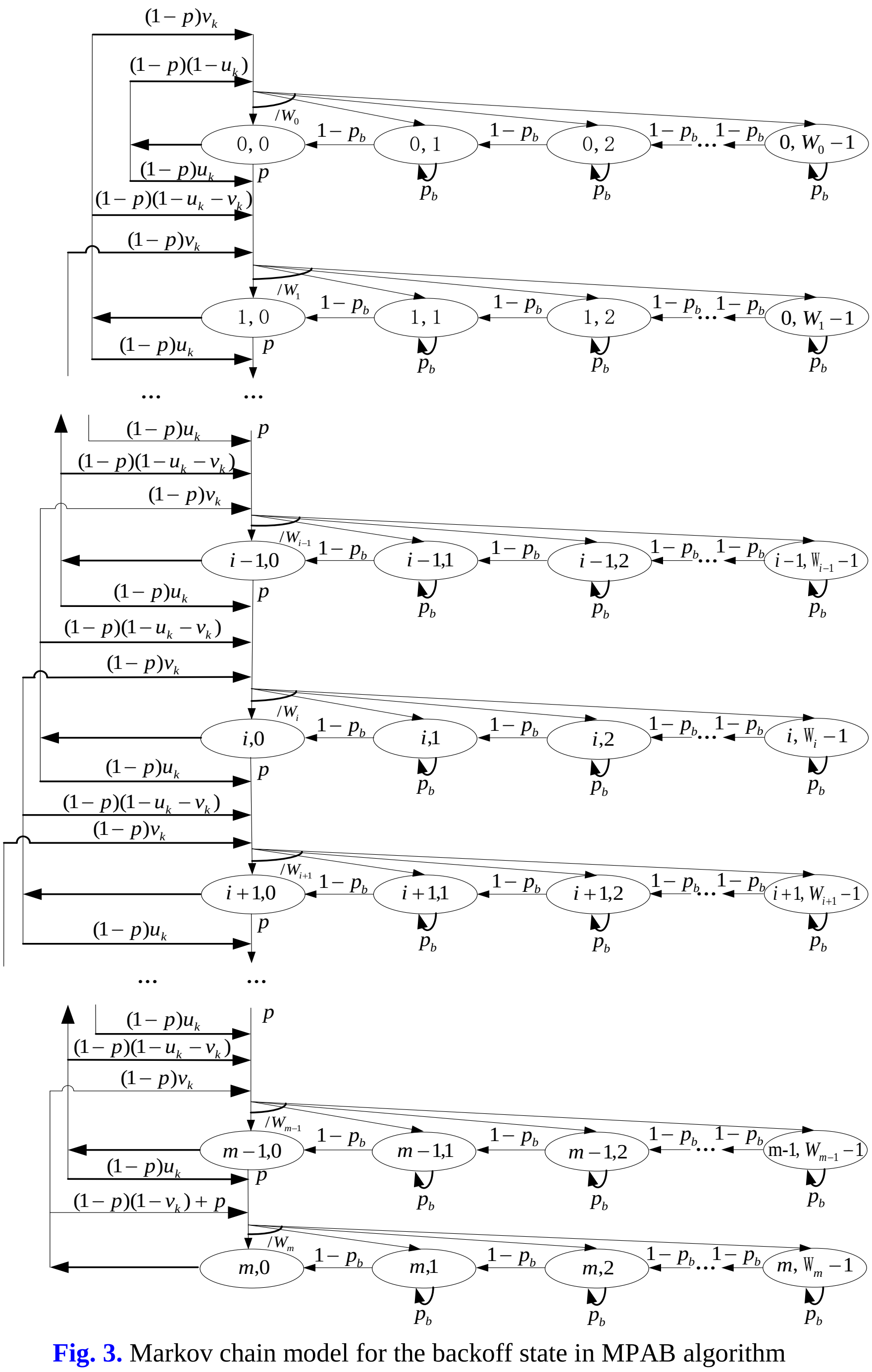


Fig. 3. Markov chain model for the backoff state in MPAB algorithm

p and p_b stand for the collision probability for every packet and the probability that the channel is busy respectively, τ represents the probability that the node sends a packet at the beginning of every slot time, and n represents the number of nodes in the network. p equals to the probability that at least one node among the other $n-1$ nodes sends a packet. Thus, the values of p and p_b coincide

$$p = 1-(1-\tau)^{n-1} \tag{1}$$

$$p_b = \sum_{i=1}^{n-1}\left[\binom{n-1}{i}\cdot\tau^i\cdot(1-\tau)^{n-1-i}\right] = 1-(1-\tau)^{n-1} \tag{2}$$

The Markov chain of the node backoff state transition is shown in **Fig. 3**. From **Fig. 3**, the one-step state transition probability in the Markov chain model can be expressed as

$$\begin{cases} P\{i,j|i,j+1\} = 1-p_b, & 0\le i\le m, 0\le j\le W_i-2 \\ P\{i,j|i,j\} = p_b, & 0\le i\le m, 1\le j\le W_i-1 \\ P\{0,j|0,0\} = \dfrac{(1-p)(1-u_k)}{W_0}, & 0\le j\le W_0-1 \\ P\{i,j|i,0\} = \dfrac{(1-p)(1-u_k-v_k)}{W_i}, & 1\le i\le m-1, 0\le j\le W_i-1 \\ P\{i,j|i+1,0\} = \dfrac{(1-p)v_k}{W_i}, & 0\le i\le m-1, 0\le j\le W_i-1 \\ P\{i,j|i-1,0\} = \dfrac{p+(1-p)u_k}{W_i}, & 1\le i\le m, 0\le j\le W_i-1 \\ P\{m,j|m,0\} = \dfrac{p+(1-p)(1-v_k)}{W_m}, & 0\le j\le W_m-1 \end{cases} \tag{3}$$

In (3), the first equation represents the probability that the backoff stage in **Fig. 3** transits backward when the channel is idle; the second equation represents the probability that the backoff counter is frozen when the channel is busy; the third equation represents the probability that the backoff stage i $(i=0)$ in **Fig. 3** transits to itself; the fourth equation represents the probability that the backoff stage i $(1\le i\le m-1)$ in **Fig. 3** transits to itself; the fifth equation represents the probability that the backoff stage i $(0\le i\le m-1)$ in **Fig. 3** transits to the latter backoff stage; the sixth equation represents the probability that the backoff stage i $(1\le i\le m)$ in **Fig. 3** transits to the former backoff stage; the last equation represents the probability that the backoff stage i $(i=m)$ in **Fig. 3** transits to itself.

From **Fig. 3**, according to the global balance, we can derive

$$\begin{cases} (1-p)v_k b_{1,0} = \left[(1-p)u_k+p\right]b_{0,0} \\ \left[(1-p)u_k+p\right]b_{i-1,0} + (1-p)v_k b_{i+1,0} = \left[(1-p)u_k+p+(1-p)v_k\right]b_{i,0}, \quad 1\le i\le m-1 \\ \left[(1-p)u_k+p\right]b_{m-1,0} = (1-p)v_k b_{m,0} \end{cases} \tag{4}$$

i.e., $b_{i,j}$ can be expressed as

$$b_{i,j}=\frac{W_i-j}{W_i}\cdot\begin{cases}(1-p)(1-u_k)b_{0,0}+(1-p)v_kb_{1,0}, & i=0, j=0\\ \frac{1}{1-p_b}\cdot\left[(1-p)(1-u_k)b_{0,0}+(1-p)v_kb_{1,0}\right], & i=0, 1\le j\le W_0-1\\ (1-p)u_kb_{i-1,0}+pb_{i-1,0}+(1-p)(1-u_k-v_k)b_{i,0}+(1-p)v_kb_{i+1,0}, & 1\le i\le m-1, j=0\\ \frac{1}{1-p_b}\cdot\left[(1-p)u_kb_{i-1,0}+pb_{i-1,0}+(1-p)(1-u_k-v_k)b_{i,0}+(1-p)v_kb_{i+1,0}\right], & 1\le i\le m-1, 1\le j\le W_i-1\\ (1-p)u_kb_{m-1,0}+pb_{m-1,0}+(1-p)(1-v_k)b_{m,0}+pb_{m,0}, & i=m, j=0\\ \frac{1}{1-p_b}\cdot\left[(1-p)u_kb_{m-1,0}+pb_{m-1,0}+(1-p)(1-v_k)b_{m,0}+pb_{m,0}\right], & i=m, 1\le j\le W_m-1\end{cases}\tag{5}$$

From (4) and (5), it can be derived that

$$b_{i,j}=\begin{cases}\frac{W_i-j}{W_i}\cdot b_{i,0}, & 0\le i\le m, j=0\\ \frac{W_i-j}{W_i}\cdot\frac{1}{1-p_b}\cdot b_{i,0}, & 0\le i\le m, 1\le j\le W_i-1\end{cases}\tag{6}$$

As the sum of all state probabilities is 1, we derive

$$1=\sum_{i=0}^{m}\sum_{j=0}^{W_i-1}b_{i,j}=\sum_{i=0}^{m}\left(b_{i,0}+\sum_{j=1}^{W_i-1}b_{i,j}\right)\tag{7}$$

According to (6) and (7), we can derive

$$\sum_{i=0}^{m}b_{i,0}+\frac{2}{1-p_b}\sum_{i=0}^{m}(W_i-1)b_{i,0}=1\tag{8}$$

From (4), we obtain

$$b_{i,0}=\left[\frac{u_k+p-pu_k}{(1-p)v_k}\right]^i b_{0,0},\quad 0\le i\le m\tag{9}$$

For simplicity of the expression, let

$$H_k=\frac{(1-p)u_k+p}{(1-p)v_k}\tag{10}$$

According to (8), (9) and (10), we can derive:

$$b_{0,0}=\frac{(1-2H_k)(1-H_k)(1-p_b)}{(2^{m+2}W_0-2p_b-2)H_k^{\,m+2}+(-2^{m+2}W_0+p_b+1)H_k^{\,m+1}+(-2W_0+2p_b+2)H_k+(2W_0-p_b-1)}\tag{11}$$

So τ can be expressed as:

$$\tau=\sum_{i=0}^{m}b_{i,0}=\sum_{i=0}^{m}H_k^{\,i}b_{0,0}\tag{12}$$

Hence,

$$\tau = b_{0,0} \cdot \frac{1-H_k{}^{m+1}}{1-H_k}$$
$$= \frac{(1-2H_k)(1-p_b)(1-H_k{}^{m+1})}{(2^{m+2}W_0 - 2p_b - 2)H_k{}^{m+2} + (-2^{m+2}W_0 + p_b + 1)H_k{}^{m+1} + (-2W_0 + 2p_b + 2)H_k + (2W_0 - p_b - 1)} \tag{13}$$

Therefore, according to (1), (2), (10) and (13), p, τ and p_b have the unique numerical solutions respectively.

4. Saturation Throughput

Here we define S_{total} as the network normalized saturation throughput for all traffic types, so S_{total} can be expressed as

$$S_{total} = \frac{\text{Average time to transmit the payload in a slot time}}{\text{Average length of a slot time}}$$
$$= \frac{P_s P_{tr} E[P]}{(1-P_{tr})\sigma + P_s P_{tr} T_s + (1-P_s) P_{tr} T_c} \tag{14}$$

Where $E[P]$ denotes the expected length of payload in a packet; T_s and T_c denotes the average time when the channel is busy in the case that the packet is transmitted successfully and unsuccessfully, respectively; P_{tr} denotes the probability that at least one node sends packets in any slot time, i.e., $P_{tr} = 1-(1-\tau)^n$; P_s denotes the probability that only one node sends packets, i.e.,

$$P_s = \frac{n\tau(1-\tau)^{n-1}}{P_{tr}} = \frac{n\tau(1-\tau)^{n-1}}{1-(1-\tau)^n} \tag{15}$$

(14) can be rewritten as

$$S_{total} = \frac{T_{data}}{T_s - T_c + 1/f(\tau)} \tag{16}$$

Where T_{data} is the time required to transmit the data packet, and

$$f(\tau) = \frac{n\tau\sigma(1-\tau)^{n-1}}{T_c - (1-\tau)^n (T_c - \sigma)} \tag{17}$$

In the network, any slot time can be attributed to three states: (1) the packet is transmitted successfully, where the probability is $P_s P_{tr}$ and the average time is T_s; (2) the packet is transmitted unsuccessfully, where the probability is $(1-P_s)P_{tr}$ and the average time is T_c; (3) the channel is idle, where the probability is $1-P_{tr}$ and the length of slot time is σ.

In IEEE 802.11 DCF, there are two access mechanisms for packet transmissions: the basic access mode and the RTS/CTS access mode. For emergency traffic, it is not suitable to adopt RTS/CTS mode due to the large latency. Therefore, in this paper, in order to save the channel resources and ensure the timeliness of information transmission, we take the basic access case as example. As is shown in **Fig. 4**, T_s and T_c can be expressed respectively as

$$\begin{cases} T_s = DIFS + H + T_D + SIFS + T_{ACK} + 2\delta \\ T_c = DIFS + H + T_D + \delta \end{cases} \tag{18}$$

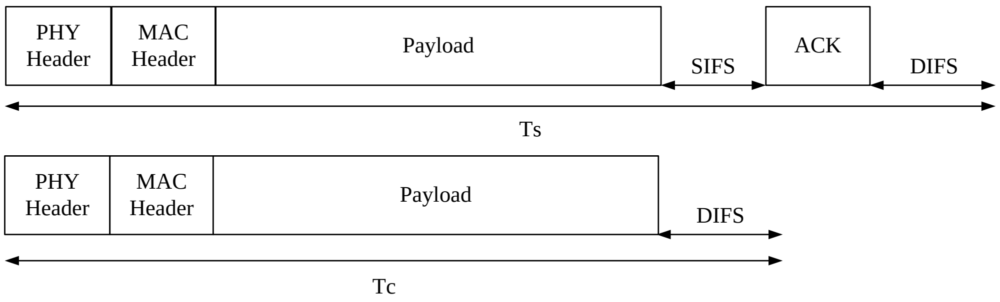


Fig. 4. Schematic diagram of T_s and T_c

Where T_D and T_{ACK} are the time length to send packet and ACK information respectively, δ is the propagation delay, $H = MAC_{hdr} + PHY_{hdr}$ is the time length to deliver the packet header.

According to the packet arrival rate λ_k $(0 \le k \le K)$ for the traffic priority k, the saturation throughput for the traffic priority k can be derived:

$$S_k = S_{total} \frac{\lambda_k}{\sum_{i=0}^{K} \lambda_i} \tag{19}$$

5. Medium Access Delay

Medium access delay $E[M]$ is the time length for the packet from waiting to be transmitted in the head of the node queue to successfully transmitted, and can be expressed as [28]

$$E[M] = E[X] \cdot E[slot] \tag{20}$$

Where $E[X]$ is the average number of time slots to deliver the packet successfully; $E[slot]$ is the average length of time slots, i.e., the denominator of (14). $E[X]$ can be expressed as:

$$E[X] = \sum_{i=0}^{m} d_i \cdot q_i \tag{21}$$

Where d_i is the average delayed time slots in backoff stage i, and q_i is the probability for the packet to arrive in the backoff stage i, thus

$$d_i = \frac{1}{W_i} \cdot \sum_{x=0}^{W_i} x = \frac{1+W_i}{2}, \quad i \in [0, m] \tag{22}$$

$$q_i = \frac{p^i - p^{m+1}}{1 - p^{m+1}}, \quad i \in [0, m] \tag{23}$$

Therefore, $E[X]$ can be expressed as

$$E[X] = \sum_{i=0}^{m} d_i \cdot q_i = \sum_{i=0}^{m} \frac{(1+W_i) \cdot (p^i - p^{m+1})}{2(1 - p^{m+1})} \tag{24}$$

6. Performance Evaluation

In this section, we will show the MPAB performance from the following three aspects.

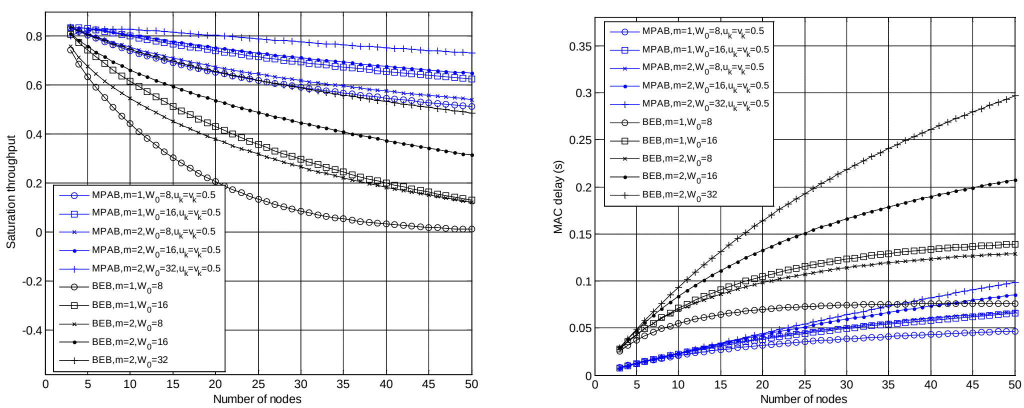
6.1 Numerical Calculations

In this part, we will give the numerical calculations of MPAB algorithm performance, and compare them with the BEB mechanism. We derive the BEB algorithm performance from Bianchi's model [7]. **Table 2** lists the MAC-layer and PHY-layer parameters used in our simulations and validations.

Table 2. Simulation parameters

Parameters	Values	Parameters	Values
DIFS	128 μs	SIFS	28 μs
MAC Header	272bits	PHY Header	128bits
ACK	112bits+ PHY Header	Propagation delay δ	1 μs
Length of slot time σ	50 μs	Size of packet load $E[P]$	1024bytes
Channel data rate	1Mbit/s		

Firstly, we show the analytical results of the MPAB algorithm performance. **Fig. 5** presents the MPAB and BEB algorithm performance versus the number of nodes under different values of m and W_0 when $u_k = v_k = 0.5$ in MPAB algorithm. **Fig. 5** shows that saturation throughput decreases and medium access delay increases as the number of nodes n increases. For both of the algorithms, with the increase of m or W_0, the saturation throughput and the medium access delay are increasing. Besides, under the same values of m and W_0, MPAB exhibits better performance than BEB algorithm.

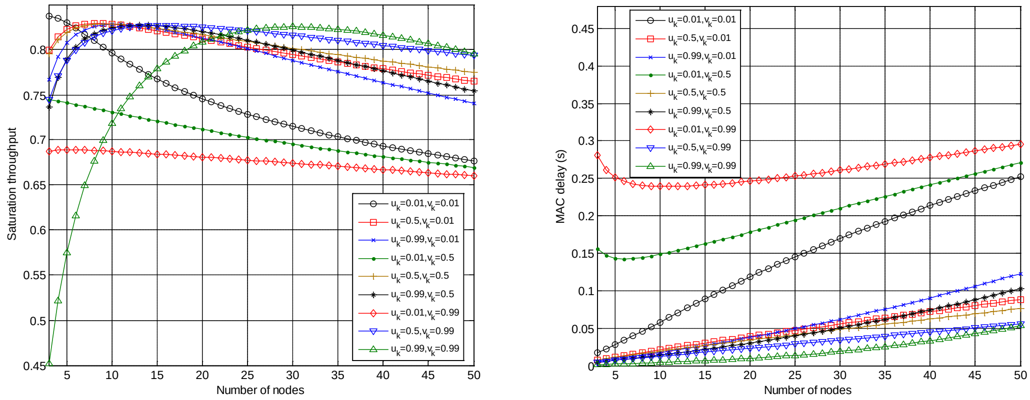


(a) Saturation throughput (b) MAC delay

Fig. 5. MPAB and BEB algorithm performance versus the number of nodes under different m and W_0

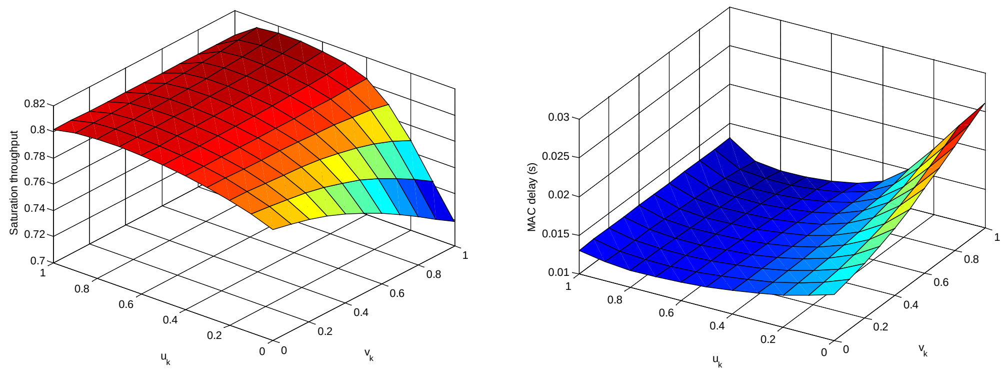
Fig. 6 shows the MPAB algorithm performance under different values of u_k and v_k when $m = 5$ and $W_0 = 32$. In **Fig. 6**, we can observe that no matter what value v_k is, with the increase of u_k, the performance improves at first, and then declines. However, when $u_k = 0.01$, the performance declines as the value of v_k increases, and when $u_k = 0.5$ or 0.99, the performance improves slightly as the value of v_k increases. Variations of saturation throughput and medium access delay versus u_k and v_k under different values of m, W_0 and n are specifically shown in **Fig. 7-10**. We can derive that in general, when the values of m, W_0 and n are smaller, the performance exhibits a minor variation with the increases of u_k and

v_k; however, when the values of m, W_0 and n become larger, the variations of u_k and v_k will incur a large change on the performance.



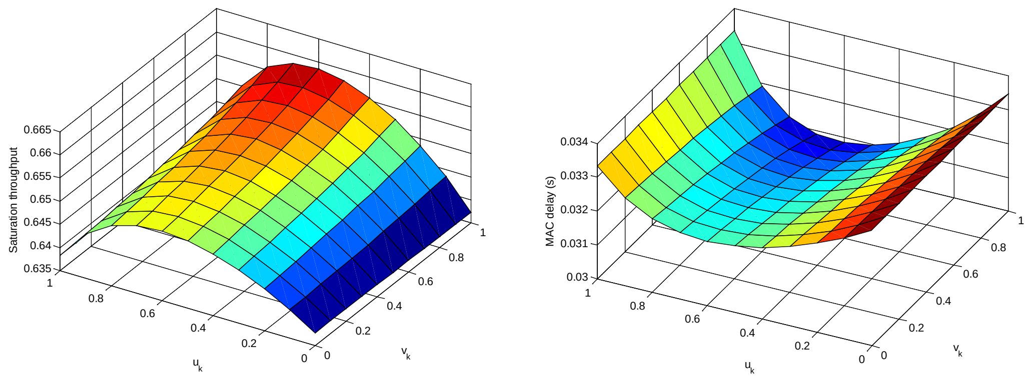
(a) Saturation throughput (b) MAC delay

Fig. 6. MPAB algorithm performance versus the number of nodes under different u_k and v_k when $m=5$ and $W_0=32$



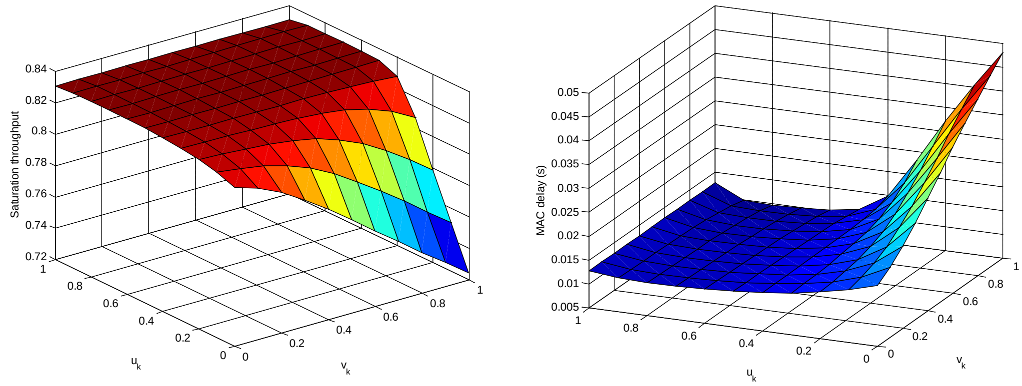
(a) Saturation throughput (b) MAC delay

Fig. 7. MPAB algorithm performance versus u_k and v_k when $m=1$, $W_0=8$, and $n=5$



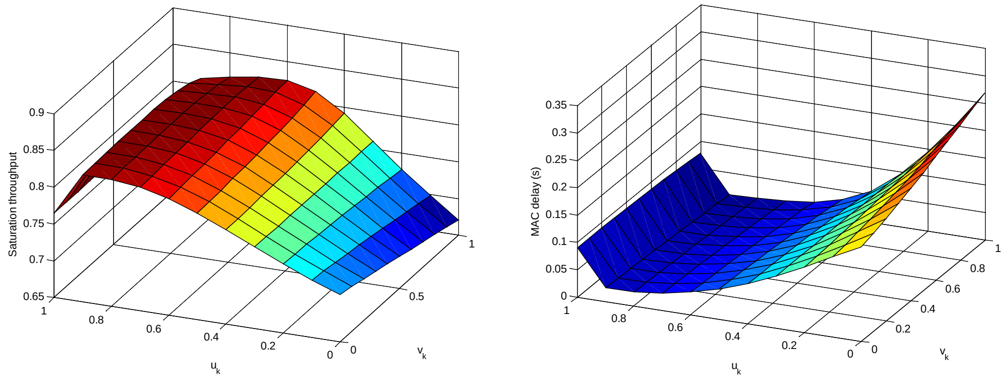
(a) Saturation throughput (b) MAC delay

Fig. 8. MPAB algorithm performance versus u_k and v_k when $m=1$, $W_0=8$, and $n=20$



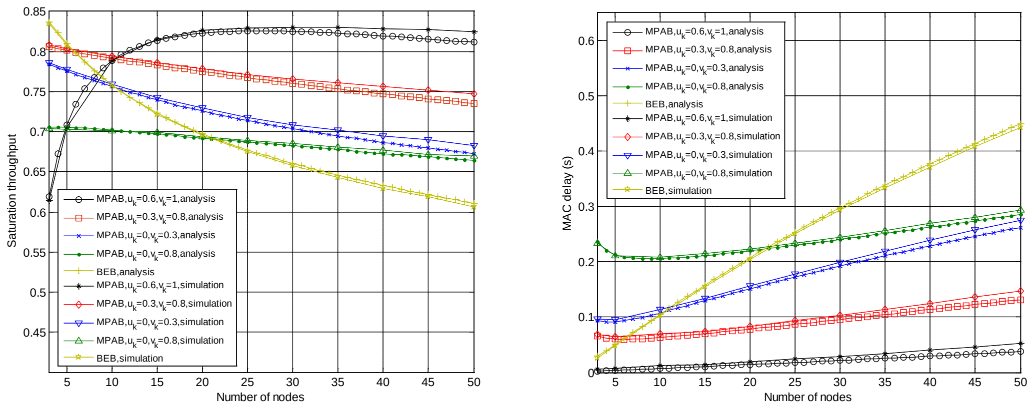
(a) Saturation throughput (b) MAC delay

Fig. 9. MPAB algorithm performance versus u_k and v_k when $m=1$, $W_0=16$, and $n=5$



(a) Saturation throughput (b) MAC delay

Fig. 10. MPAB algorithm performance versus u_k and v_k when $m=5$, $W_0=32$, and $n=30$



(a) Saturation throughput (b) MAC delay

Fig. 11. Simulation against analysis for MPAB and BEB algorithm under different u_k and v_k when $m=5$ and $W_0=32$

6.2 Simulations

In this part, we will simulate the MPAB and BEB algorithm in NS-2.32 platform, and compare the results with the above numerical calculations from mathematical models, validating the correctness of the theoretical derivation.

The size of simulation scenario is set as 500×500m^2. The node initial locations obey the uniform distribution in the scenario, and then move based on the most popular mobility model for wireless mobile networks, the Random Waypoint (RWP) model with the speed interval $[0,5]$ m/s. The communication range of nodes is set to 250m. The MAC-layers of the two schemes both adopt the IEEE 802.11 DCF, and the unique difference between both schemes lies in the backoff algorithm, i.e., one scheme adopts the MPAB algorithm, and the other one uses the traditional BEB algorithm. Other main simulation parameters are listed in **Table 2**. After simulation, the average values of saturation throughput and medium access delay are statistically calculated upon 10 times of random simulation results, and compared with the theoretical results, which are shown in **Fig. 11**. As can be concluded from **Fig. 11**, on one hand, compared with the BEB algorithm, the saturation throughput is larger, and medium access delay is lower using MPAB algorithm, and grand performance improvement can be observed. Furthermore, the BEB algorithm performance is influenced more greatly by the number of nodes, while the effect of the number of nodes on the MPAB algorithm is relatively less. On the other hand, the theoretical results match well with the simulation results, validating the accuracy of the theoretical model on MPAB algorithm.

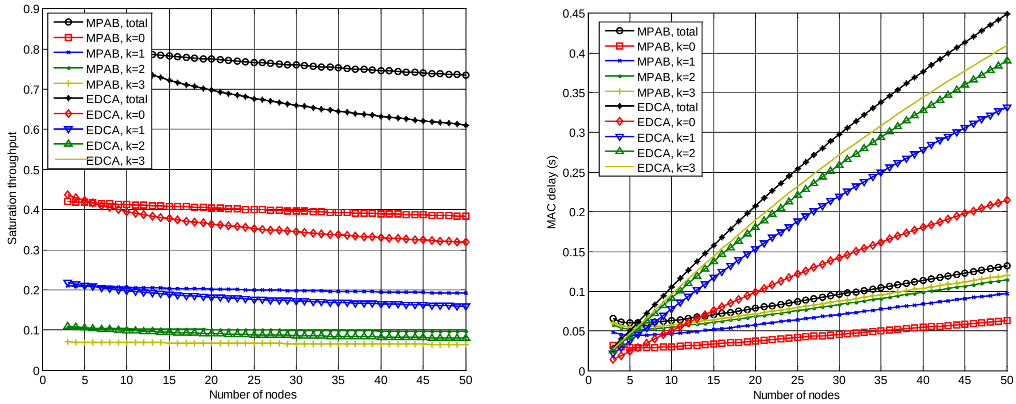
6.3 Example of the Multi-priority Service Differentiation in MPAB

In the final part, we will give an example of the multi-priority service differentiation in the MPAB algorithm. Here we designate four traffic types as the EDCA protocol, i.e., voice, video, best effort, and background. When $m=5$, $W_0=32$ and $n=30$, according to the QoS requirement of every priority traffic, we can obtain the values of u_k and v_k from the above analytical or simulation results, as is shown in **Table 3**. In practical applications, we can derive the proper values of u_k and v_k according to the QoS requirement of a certain traffic type using our analytical model of the MPAB algorithm.

According to the parameters in **Table 3**, we compare the performance of every traffic type in MPAB and EDCA with the same parameters for theoretical calculations and simulations. In these calculations and simulations, the ratio of packet arrival rate for every traffic type is 6:3:1.5:1, as is the recommended parameters in EDCA protocol [9]. The results are shown in **Fig. 12** and **Fig. 13**. From them, we can acquire that the performance of MPAB is better than EDCA.

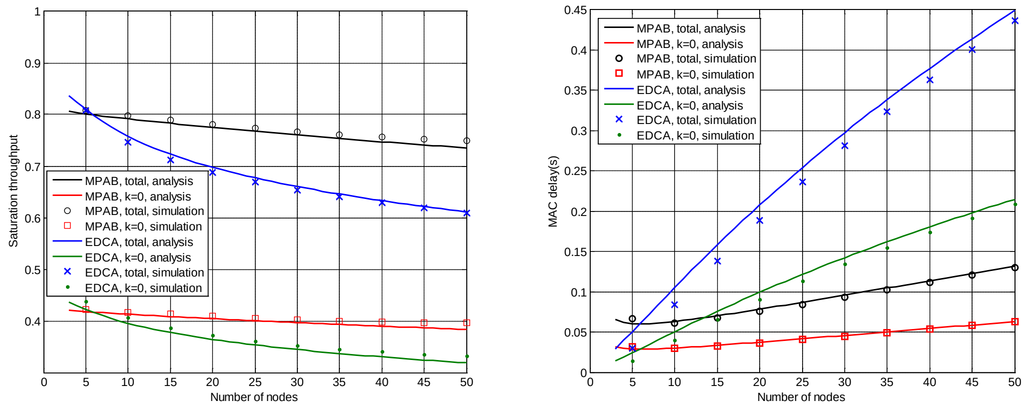
Table 3. Example of multi-priority service differentiation in MPAB algorithm when $m=5$, $W_0=32$, and $n=30$

Priority	Designation	QoS requirement		u_k	v_k	Performance	
		Saturation throughput	MAC delay (s)			Saturation throughput	MAC delay (s)
$k=0$	Voice	>0.39	<0.05	0.6	1	0.3967	0.0458
$k=1$	Video	>0.18	<0.08	0.3	0.8	0.1983	0.0708
$k=2$	Best effort	>0.09	<0.09	0	0.3	0.0992	0.0833
$k=3$	Background	>0.06	<0.09	0	0.8	0.0661	0.0875



(a) Saturation throughput (b) MAC delay

Fig. 12. Performance of every traffic type in MPAB with $m = 5$ and $W_0 = 32$ and EDCA protocol



(a) Saturation throughput (b) MAC delay

Fig. 13. Simulation against analysis for MPAB with $m = 5$ and $W_0 = 32$ and EDCA protocol

7. Conclusion

In the paper, we have designed a novel backoff mechanism in MAC-layer with high flexibility, strong scalability, and multi-priority service differentiation for the wireless mobile networks, named the multi-priority service differentiated and adaptive Backoff mechanism. Based on the IEEE 802.11 DCF, the proposed algorithm chooses next backoff stage adaptively according to whether the packet is sent successfully, the forwarding and receding transition probabilities of backoff stages and the value of the channel collision flag. Any number of priority classes can be supported by the algorithm. Different priority traffic can be differentiated by different values of the forwarding and receding transition probabilities of backoff stages, and the transition probabilities can be updated at any time. Theoretical model and simulation results show that the performance of the algorithm is greatly improved compared with the BEB and EDCA protocol, and can meet the requirement of the transmission of any types of information in wireless mobile networks. The future work is to further analyze the performance indexes of the algorithm, such as fairness, and apply it into the multi-channel MAC protocol in wireless mobile networks.

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Bo Zheng received his M.Sc. degree in 2008, and Ph.D. degree in 2011 from Telecommunication Engineering Institute in Air Force Engineering University, Xi'an, China, respectively. He is now a lecturer in Information and Navigation Institute, Air Force Engineering University. His research interests mainly focus on wireless mobile ad hoc networks and aeronautical data links.

Hengyang Zhang received the Master Degree in Telecommunication Engineering Institute from Air Force Engineering University in 2004, and the Ph.D. degree in Electronics Engineering Institute from National University of Defense and Technology in 2008. Now, he is an associate professor in Information and Navigation Institute, Air Force Engineering University. His current research interests are in ad hoc networks, wireless sensor networks, and aeronautical data links

Kun Zhuo received his M.Sc. degree in 2011, and Ph.D. degree in 2015 from Information and Navigation Institute in Air Force Engineering University, respectively. He is now a lecturer in PLA 93995 Unit, Xi'an, China. His research interest is mobility model, routing and MAC protocols in ad hoc networks.

Huaxin Wu received his Ph.D. degree in 2011 from Telecommunication Engineering Institute in Air Force Engineering University. He is now a lecturer in Air Force Early Warning Academy, Wuhan, China. His research interests are in communication networks, computer networks and wireless communications.