# A Simple Adaptive p-persistent MAC Scheme for Service Differentiation and Maximum Channel Utilization

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*Abstract:* - In this paper, we propose an adaptive p-persistent MAC scheme, named QDA-MAC (QoS differentiation based adaptive MAC scheme), for WLAN to maximize the channel utilization and provide the service differentiation among different traffic stations. Specifically, different from the previous works, the proposed scheme does not need to estimate the number of active stations for each priority class and still achieves the channel utilization close to its optimal value by exploiting a new parameter, persistent factor, whose optimal value can dynamically follow the change of the load based on a simple estimation of the network status. At the same time, the transmission probability of each priority class can be updated by optimal persistent factor. Simulation and numerical results show that QDA-MAC can achieve much higher channel utilization and shorter delay than standard IEEE 802.11 DCF and IEEE 802.11e EDCA in all different WLAN environments.

*Key-Words:* - QoS differentiation; p-persistent; persistent factor; adaptive scheme; transmission attempt

## 1 Introduction

Wireless local area networks (WLAN) have been widely deployed in recent years. In WLANs, the most important standard is IEEE802.11 [1], in which the fundamental medium access control(MAC) scheme is distributed coordination function (DCF), which is a carrier sense multiple access with collision avoidance (CSMA/CA) protocol. The enhanced distributed channel access (EDCA) scheme [13] in the IEEE 802.11e standard is proposed to provide prioritized quality of service (QoS). Although the goal of IEEE 802.11e EDCA is to enhance the DCF access mechanism of IEEE 802.11 and to support service differentiation, the performance obtained is not optimal since EDCA parameters can not be adapted to the network conditions. This paper focuses on the adaptation of protocol parameters for each priority class according to the network conditions.

Previous works have shown that an appropriate tuning of the IEEE 802.11 back-off algorithm can significantly increase the channel utilization [2,7,10,15]. Specifically, to study the capacity of the IEEE 802.11 protocol, a p-persistent IEEE 802.11 protocol [2] was introduced. This protocol adopts a p-persistent back-off strategy to approximate the original back-off in the standard protocol. Recently, based on the p-persistent version of the IEEE 802.11 protocol, related adaptive MAC algorithms [3,8,9,11], which integrate the measurement and estimate of the network conditions into the adaptation of protocol parameters at run-time, can effectively enhance the protocol performance. However, in heavy load case, theses algorithms estimating the number of active stations for each priority class are not robust enough to be fit for dynamic WLAN environments. Motivated by this point, we aim to simplify adaptive algorithm by avoiding the estimation of the number of each class station but still achieve dynamic optimization of the channel utilization and provide service difference among different traffic classes.

As pointed out in [7], in a heterogeneous WLAN, the optimal transmission probability set satisfies the throughput ratio among different traffic classes and also maximizes the total channel utilization. However, the back-off algorithm in [7] is not adaptive and has high computational complexity. On the other hand, adaptive algorithms proposed in [2,3,11] dynamically adapt the transmission probability for each station to achieve the maximum throughput based on the network measurement. But only one traffic class is considered, all stations in the network transmit with the same probability. Consequently, no service differentiation is provided. Although the back-off tuning algorithm analyzed in [8,9] can maximum the total channel utilization and provide the service differentiation, it is extremely complex because the estimate of the number of prioritized traffic stations is achieved by estimating the network traffic and taking into account the p value currently used by each traffic class. Noticeably, higher computational complexity results in larger probability of the performance instability of the heterogeneous WLAN because interdependences exist among many quantities that need to be estimated for characterizing the channel status.

In this paper, to avoid the computational complexity of acquiring instantaneous network conditions, an adaptive p-persistent MAC scheme for a heterogeneous WLAN, named QDA-MAC (QoS differentiation based adaptive MAC scheme), is developed to maximize the total channel utilization and provide QoS differentiation for multiple traffic classes. The major difference from the previous works is that QDA-MAC, in which a new parameter called persistent factor is introduced, does not need any estimate of the number of prioritized traffic stations. Based on the simple real-time network measurements, the proposed scheme can quickly adapt the persistent factor to the desirable value in order to achieve maximum channel utilization. And then optimal persistent factor can update the transmission probability for each priority class to satisfy the QoS differentiation. QDA-MAC scheme tremendously reduces the computational complexity but is still able to maintain the utilization close to its optimal value. Detailed simulation results shows that QDA-MAC can effectively achieve the performance goal under a variety of network conditions.

## 2 QoS differentiation based adaptive p-persistent MAC scheme — QDA-MAC

This section focuses on the QDA-MAC scheme in detail. Quasi-optimal condition shows that the optimal utilization state is characterized by the balancing between collisions' duration and idle times inside the average virtual transmission time [2,12]. The operating point of the proposed adaptive scheme is identified by the quasi-optimal condition. Moreover, the proposed scheme exploits persistent factor that is defined as a function of transmission probabilities of different traffic classes. Therefore, the adaptation of the transmission probabilities is based on the optimal persistent factor and the proposed adaptive method, which will be illustrated in the following sections.

### 2.1 Quasi-optimal condition

For a network that supports multiple traffic classes, a station that transmits class-i traffic is classified as a class-i station. In a WLAN, the mobile station joins and leaves the network randomly. In order to achieve the maximum channel utilization and QoS differentiation in a dynamic WLAN environment, the transmission probability of each class should be dynamically adapted. Paper [2] points out a quasi-optimal condition which the channel utilization is very closed to its theoretical maximum bound when the average time spent on idle stage is equal to the average time spent on collisions, i.e.,

$$E[T_c]|_{collision} \cdot E[N_c] = (E[N_c]+1)\cdot E[Idle] \qquad \text{and} \qquad E[T_c] = E[Idle] \tag{1}$$

By using condition (1) as the maximum channel utilization constraint, the complexity of adaptation of the optimal transmission probability set can be greatly reduced. The major notations in (1) are listed below:

- $E[T_c]|_{collision}$: average collision time given that a collision occurs;
- $E[N_c]$: average number of collisions;
- $E[T_c]$: average collision time in a virtual transmission time, $E[T_c] = E[T_c]|_{collision}\left[E[N_c]/(E[N_c]+1)\right]$;
- $E[Idle]$: average consecutive idle time slots;
- $r_{i,j}$: the utilization ratio between a class-i station and a class-j station;

The following equations of $E[N_c], E[Idle]$ and $\overline{r_{i,j}}$ have been derived in [7]:

$$E[N_c] = \frac{1-\prod_{i=0}^{M-1}(1-p_i)^{N_i}}{\sum_{i=0}^{M-1} N_i p_i (1-p_i)^{N_i-1}\prod_{j=0,j\neq i}^{M-1}(1-p_j)^{N_j}} - 1 \tag{2}$$

$$E[Idle] = \frac{\prod_{i=0}^{M-1}(1-p_i)^{N_i}}{1-\prod_{i=0}^{M-1}(1-p_i)^{N_i}}\cdot m \tag{3}$$

$$\overline{r_{i,j}} = \frac{\rho_i/N_i}{\rho_j/N_j} = \frac{E[L_i]}{E[L_j]}\cdot\frac{p_i(1-p_j)}{p_j(1-p_i)} \tag{4}$$

Let m, $L_i$, $p_i, N_i$ and $\rho_i$ denote the duration of an empty slot time, the packet length, the transmission probability, the number of class-i traffic in the network and the utilization attained by class-i traffic, respectively.

### 2.2 Persistent factor $p*$

In a WLAN with only one traffic class, the transmission probability of each station is equal to persistent factor. On the other hand, persistent factor is a function of M transmission probabilities of priority classes when a WLAN supports a total of M different traffic classes. Let $p*$ denote persistent factor and it can be expressed by

$$p* = P(p_0, p_1, \cdots p_{M-1}) \tag{5}$$

The probability $f$ that the channel is idle can be given as:

$$f(p_0, p_1, \cdots p_{M-1}) = \prod_{i=0}^{M-1}(1-p_i)^{N_i} \tag{6}$$

By exploiting the Maclaurin formula, we can approximate $f$ as

$$f(p_0, p_1, \cdots p_{M-1}) \approx 1 - \frac{\sum_{i=0}^{M-1} N_i}{M}\left(\sum_{i=0}^{M} p_i - \sum_{\substack{i,j=0\\ j>i}}^{M-1} p_i p_j + \sum_{\substack{i,j,k=0\\ k>j>i}}^{M-1} p_i p_j p_k - \cdots\right) \tag{7}$$

We substitute $f(p_0, p_1, \cdots p_{M-1})$ in equation (3) and the approximate expression of $E[Idle]$ is able to be obtained:

$$E[Idle] \approx \frac{1-\frac{1}{M}(\sum_{i=0}^{M-1} N_i)\cdot p*}{\frac{1}{M}(\sum_{i=0}^{M-1} N_i)\cdot p*}\cdot m \tag{8}$$

Where $p*$ is persistent factor

$$p* = \left(\sum_{i=0}^{M-1} p_i - \sum_{\substack{i,j=0\\ j>i}}^{M-1} p_i p_j + \sum_{\substack{i,j,k=0\\ k>j>i}}^{M-1} p_i p_j p_k - \cdots\right)$$

We assume that $E[T_c]|_{collision} = l$. This approximation is based on the results presented in [11] indicating that, when a network operates close to its optimal behavior, the probability that more than two traffic stations collide is practically negligible. Therefore we can consider the approximation $E[T_c]|_{collision} = \max\{L_1, L_2\} = l$, where $L_i$ is a packet size of class-i traffic. We can also substitute $f(p_0, p_1, \cdots p_{M-1})$ in the expression of $E[T_c]$ as follows:

$$E[T_c] = l\cdot\frac{E[N_c]}{E[N_c]+1} \approx l\cdot\frac{1}{2}\cdot\frac{1}{M}(\sum_{i=0}^{M-1} N_i)\cdot p* \tag{9}$$

Optimal persistent factor can be derived from equation (8) and (9) by using condition (1) as the maximum channel utilization constraint. Adaptation of the optimal transmission probability set of each traffic class can be achieved by optimal persistent factor in equation (4) which satisfies the QoS differentiation.

To verify the relative error of the approximate relationship for small and medium $N_i$ value, we numerically solved both (7) and (9) for a wide range of $N_i$ value. When we consider only two priority classes in the network, from equation (6), we have $f(p_0, p_1) = (1-p_0)^{N_0}(1-p_1)^{N_1}$, where $p_0 > p_1$. The relative error between the exact $f(p_0, p_1)$ value and the approximate $f(p_0, p_1)$ value that solve (7), say $f^*(p_0, p_1)$, can be obtained by choosing different $N_i$ value. Figure 1 and figure 2 also show the relative error between the $E[Idle]$ value and the average idle time computed by using $f^*(p_0, p_1)$ in (8). Likewise, similar results can also be given for the $E[T_c]$ value. Likewise, Results in the figure 1 and figure 2 indicate that equation (7) provides accurate estimate also for small-medium $N_i$ value. Specifically, figures provide the approximation of $f(p_0, p_1)$ with a relative error that always lower than 1%.

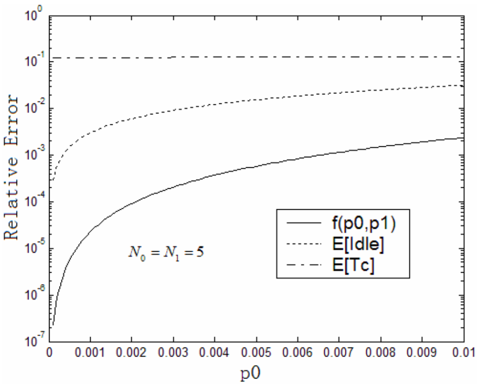

Figure 1 relative error ( $N_0 = N_1 = 5$ )

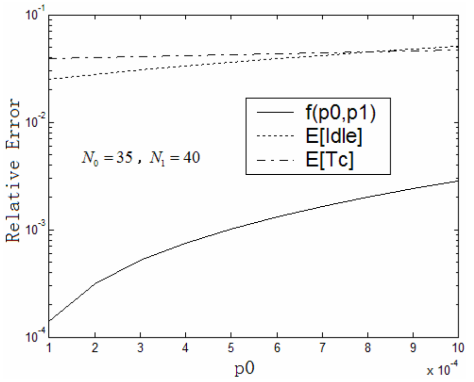

Figure 2 relative error ( $N_0 = 35$, $N_1 = 40$ )

## 2.3 Adaptive method

Equation (1) provides a robust criterion to afford, at run-time, the channel utilization maximization. To achieve this, QDA-MAC updates the estimate of the network status (i.e. $E[Idle]$ and $E[T_c]$) at the end of each (successful or colliding) transmission attempt.

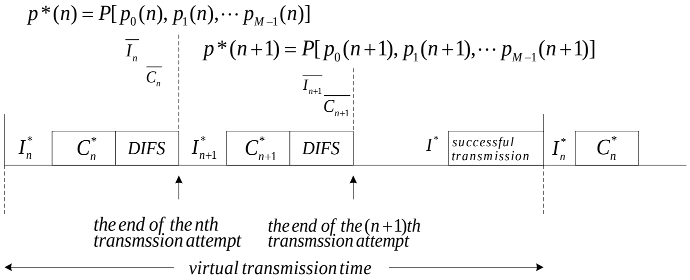

Figure 3 transmission attempt

To better clarify the operations performance by a traffic behavior let us refer to figure 3. During the (n+1)th transmission attempt, it has the following information:

- $I_{n+1}^*$: the length of the (n+1)th idle period;
- $C_{n+1}^*$: the collision cost during the (n+1)th transmission attempt;
- $p_i(n+1)$, $(0 \le i \le M-1)$: optimal transmission probability of class-i traffic at the end of the (n+1)th transmission attempt;
- $p^*(n+1)$: optimal persistent factor at the end of the (n+1)th transmission attempt, $p^*(n+1) = P[p_0(n+1), p_1(n+1), \cdots p_{M-1}(n+1)]$;
- $\overline{I_{n+1}}$: an estimate of the average time spent listening the channel, $\overline{I_{n+1}} = E[idle](n+1)$;
- $\overline{C_{n+1}}$: an estimate of the average collision length, $\overline{C_{n+1}} = E[T_c](n+1)$.

Accordingly, the moving average collision time is updated after each transmission attempt, failure or success:

$$\overline{C_{n+1}} = \alpha \overline{C_n} + (1-\alpha) C_{n+1}^* \tag{10}$$

Where $\alpha$ is the adaptation smoothing factor, which can influence significantly adaptive performance of the proposed scheme. Upon each transmission attempt, $I_{n+1}^*$ can be measured and the average consecutive idle time $I_{n+1}$ is updated:

$$\overline{I_{n+1}} = \alpha \overline{I_n} + (1-\alpha) I_{n+1}^* \tag{11}$$

Therefore, if $\overline{I_{n+1}} \neq \overline{C_{n+1}}$ during the (n+1)th transmission attempt, our control strategy searches a new persistent factor $p^*(n+1)$ such as to have $\overline{I_{n+1}} = \overline{C_{n+1}}$ at the end of the (n+1)th transmission attempt. If $\overline{I_{n+1}} > \overline{C_{n+1}}$, we should increase the $p^*$ value, otherwise we should decrease it. We let $p_{temp}^*$ denote updated persistent factor value at the end of each transmission attempt. Lemma 1 below shows how optimal $p_{temp}^*$ can be derived by using the $p^*(n)$ value.

***Lemma 1*** The updated $p_{temp}^*$ value at the end of the (n+1)th transmission attempt can be obtained by solving the following equation:

$$p_{temp}^* = \frac{\sqrt{4\overline{C_{n+1}}(\overline{I_{n+1}} + m) + m^2} - m}{2\overline{C_{n+1}}} \cdot p^*(n) \tag{12}$$

Where m is the duration of an empty slot time and $p^*(n)$ denotes optimal persistent factor at the end of the n-th transmission attempt.

***Proof:*** the proof is derived by following assumption:

$$\tfrac{1}{M}\left(\sum_{i=0}^{M-1} N_i\right) \cdot p_{temp}^* = x \text{, where } \tfrac{1}{M}\left(\sum_{i=0}^{M-1} N_i\right) = A.$$

We assume that during the (n+1)th transmission attempt, $\overline{I_{n+1}} \neq \overline{C_{n+1}}$, by using optimal condition (1), equation (8) and (9) we can obtain:

$$\frac{l}{2m} x^2 + x - 1 = 0$$

Solving this equation, $x$ can be expressed as:

$$x = \frac{-1 + \sqrt{1 + \frac{2l}{m}}}{l/m} \Rightarrow p_{temp}^* = \frac{-1 + \sqrt{1 + \frac{2l}{m}}}{Al/m} \tag{13}$$

Table 1： $p^*_{temp}$， $\rho^*_u$ by using QDA-MAC adaptive method and numerically exact value $p^*_{num}$， $\rho_{num}$

| | | QDA-MAC | | | | Numerically exact values | | | | Relative error |
|---|---|---|---|---|---|---|---|---|---|---|
| $N_0=10$ | $N_1=10$ | $p^*_{temp}$ | $p_0$ | $p_1$ | $\rho^*_u$ | $p^*_{num}$ | $p_{num\_0}$ | $p_{num\_1}$ | $\rho_{num}$ | $(\rho_{num}-\rho^*_u)/\rho_{num}$ |
| 20 | 10 | 0.0059 | 0.0039 | 0.0020 | 0.8002 | 0.0056 | 0.0037 | 0.0019 | 0.8003 | 1.2495e-4 |
| 30 | 10 | 0.0045 | 0.0030 | 0.0015 | 0.7993 | 0.0040 | 0.0027 | 0.0013 | 0.8000 | 8.7500e-4 |
| 40 | 10 | 0.0036 | 0.0024 | 0.0012 | 0.7988 | 0.0031 | 0.0021 | 0.0010 | 0.7997 | 1.1254e-3 |
| 50 | 10 | 0.0030 | 0.0020 | 0.0010 | 0.7984 | 0.0025 | 0.0017 | 8.50e-4 | 0.7996 | 1.5008e-3 |
| 60 | 10 | 0.0025 | 0.0017 | 8.34e-4 | 0.7982 | 0.0021 | 0.0014 | 7.13e-4 | 0.7995 | 1.6260e-3 |
| 70 | 10 | 0.0022 | 0.0015 | 7.34e-4 | 0.7979 | 0.0019 | 0.0012 | 6.16e-4 | 0.7995 | 2.0012e-3 |
| 80 | 10 | 0.0020 | 0.0013 | 6.67e-4 | 0.7981 | 0.0016 | 0.0011 | 5.37e-4 | 0.7994 | 1.6262e-3 |
| 90 | 10 | 0.0018 | 0.0012 | 6.00e-4 | 0.7975 | 0.0014 | 9.67e-4 | 4.79e-4 | 0.7994 | 2.3768e-3 |

After some algebraic manipulations in equation (9), $\overline{C_n}$ is derived as follows:

$$\overline{C_n} = l \cdot \frac{Ap^*_n}{2} \Rightarrow l = \frac{2\overline{C_n}}{Ap^*_n} \tag{14}$$

Furthermore, from equation (8) $\overline{I_n}$ can be written as:

$$\overline{I_n} = \frac{1 - Ap^*_n}{Ap^*_n} \Rightarrow Ap^*_n = \frac{m}{\overline{I_n} + m} \tag{15}$$

By substituting $\overline{C_n}$ and $\overline{I_n}$ in (13), after some algebraic manipulations the expression of equation (12) can be obtained. This concludes the proof.

Lemma 1 shows if there is no change of the load in the network, i.e., $\overline{I_{n+1}} = \overline{C_{n+1}}$ during the (n+1)th transmission attempt, we can obtain $p^*_{temp} = p^*(n)$. On the other hand, if $\overline{I_{n+1}} \neq \overline{C_{n+1}}$ due to the change of the number of competing traffic stations, $p^*_{temp}$ can be dynamically adapted to the network conditions based on the $p^*(n)$ value. Thus, the proposed scheme exploits optimal persistent factor to achieve maximum channel utilization in a timely manner. Finally, to avoid harmful fluctuations of the persistent factor value, we utilize a smoothing factor, and hence $p^*(n+1)$ is:

$$p^*(n+1) = \alpha\, p^*(n) + (1-\alpha)\, p^*_{temp} \tag{16}$$

Once $p^*(n+1)$ is known, the transmission probability $p_i(n+1)$ of the class-i traffic at the end of the (n+1)th transmission attempt can be obtained from following adaptive equation:

$$\Big(\sum_{i=0}^{M} p_i(n+1) - \sum_{\substack{i,j=0\\ j>i}}^{M-1} p_i(n+1)\, p_j(n+1) + \sum_{\substack{i,j,k=0\\ k>j>i}}^{M-1} p_i(n+1)\, p_j(n+1)\, p_k(n+1) - \cdots\Big) = p^*(n+1) \tag{17}$$

We can numerically verify adaptive method of the QDA-MAC scheme by adopting the persistent factor and assume that there are two traffic classes in the network. Let $p_0$ and $p_1$ denote transmission probabilities of high priority class and low priority class, respectively. We have $p_0 > p_1$. Class-0 and class-1 all start with 10 stations. Let 10 more class-0 stations join the network step by step, we can compare $p^*_{temp}$ value which is derived by QDA-MAC adaptive method with $p^*_{num}$ value which is solved numerically in both equation (2) and (3). On the other hand, we can also show the relative error between the channel utilization $\rho^*_u$ and numerically exact $\rho_{num}$ value of the channel utilization measured when all the station adopt the $p^*_{num}$ value. Results presented in the Table 1 indicate that adaptive method of the QDA-MAC scheme provides accurate estimates compared with numerically exact values. Specifically, the average error between $p^*_{temp}$ and $p^*_{num}$ is only 0.0004. Meanwhile, the relative error related to the $p^*_{temp}$ approximation is always a magnitude lower than the relative error related to the utilization $\rho^*_u$ approximation. Therefore, the method which dose not estimate the number of prioritized traffic stations can tremendously simplify the computation and still maintain the utilization close to its optimal value.

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$p^*(n)$: optimal persistent factor during n-th transmission attempt,
        $p^*(n) = P[p_0(n), p_1(n), \cdots p_{M-1}(n)]$
Begin:
  1) $I^*_{n+1}$: the idle period during the (n+1)th transmission attempt;
  2) $C^*_{n+1}$: the collision cost during the (n+1)th transmission attempt;
  3) $\overline{I_{n+1}} = \alpha\overline{I_n} + (1-\alpha)I^*_{n+1}$
  4) $\overline{C_{n+1}} = \alpha\overline{C_n} + (1-\alpha)C^*_{n+1}$
  5) $p^*_{temp} = \frac{\sqrt{4\overline{C_{n+1}}(\overline{I_{n+1}}+m)+m^2} - m}{2\overline{C_{n+1}}} \cdot p^*(n)$
  6) $p^*(n+1) = \alpha\, p^*(n) + (1-\alpha)\, p^*_{temp}$
  7) compute $p_i(n+1)$ based on the following M equations by using
     numerical method:
        $\begin{cases} \Big(\sum_{i=0}^{M} p_i(n+1) - \sum_{i,j=0;\, j>i}^{M-1} p_i(n+1)p_j(n+1) + \sum_{i,j,k=0;\, k>j>i}^{M-1} p_i(n+1)p_j(n+1)p_k(n+1) - \cdots\Big) = p^*(n+1) \\ \overline{r_{i,j}} = \frac{\rho_i/N_i}{\rho_j/N_j} = \frac{E[L_i]}{E[L_j]} \cdot \frac{p_i(n+1)(1-p_j(n+1))}{p_j(1-p_i(n+1))} \end{cases}$
  8) Solve the initial contention window size of class-i by mapping
     p-persistent model onto standard 802.11MAC mechanism:
        $p_i(n+1) \rightarrow CW\min(i)(n+1)$
End.
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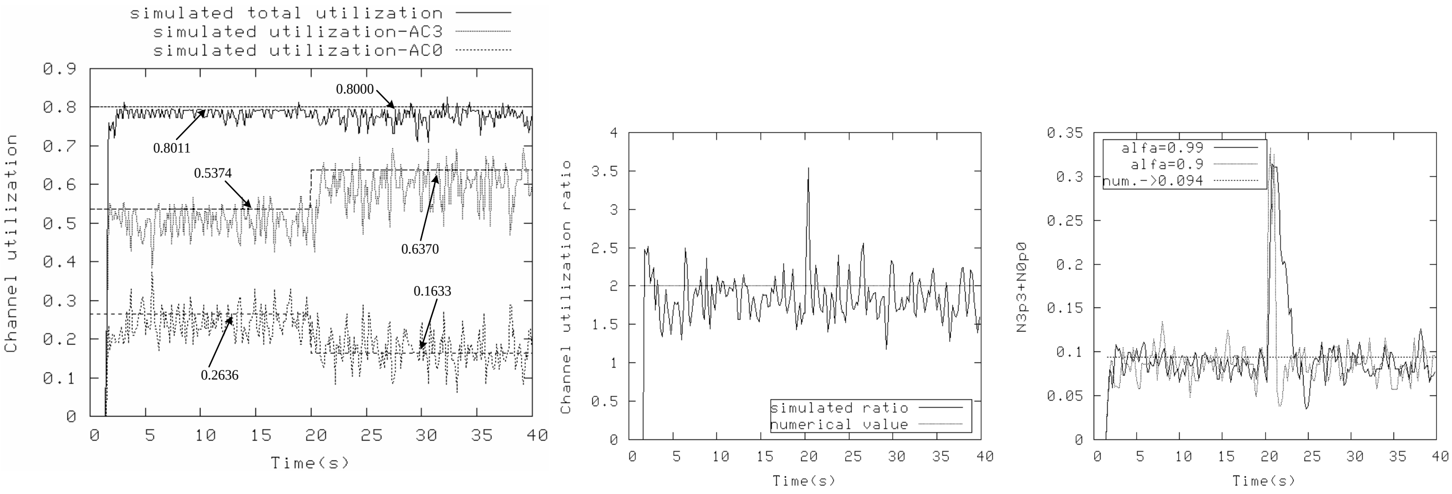
Figure 4 QDA-MAC adaptive algorithm



(a) Channel utilization (b) utilization ratio 2.0 (c) adaptive performance

Figure5 QDA-MAC adaptive performance

### 2.4 QDA-MAC adaptive algorithm

Figure 4 summarizes the algorithm step for the QDA-MAC scheme presented in section 2. The steps performed independently by each class station at the end of (n+1)th transmission attempt to compute the optimal transmission probability of each traffic class for the current network and load conditions based on the optimal persistent factor during n-th transmission attempt.

## 3 Performance evaluations

Simulation experiments have been set up in ns-2 to evaluate the performance of the proposed QDA-MAC scheme. The performance analysis is carried out by simulations under the assumption of an ideal channel with no transmission errors and no hidden terminals, i. e. all stations are within the transmission range of one another. Each wireless station operates at IEEE 802.11 [1] ad-hoc DCF mode. Table 2 summarizes the operation parameter values of the WLAN analyzed in the paper. A station in the network can be either a class-3 (let AC3 denote class-3 real-time traffic) or a class-0 (let AC0 denote class-0 best-effort traffic) station. The target channel utilization ratio between two different traffic stations is 2.0. We study main performance metrics such as the channel utilization and average MAC delay for several packet lengths and number of prioritized traffic stations. Thus the effectiveness of QDA-MAC can be analyzed with different network configurations.

Table 2 WLAN operation parameters

| | |
|---|---|
| Channel bit rate | 2Mbps |
| PLCP date rate | 1Mbps |
| Slot time | 20 $\mu s$ |
| SIFS | 10 $\mu s$ |
| DIFS | 50 $\mu s$ |
| RTS | 160bits+192bits |
| CTS, ACK | 112bits+192bits |
| PHY header | 192bits |
| MAC header | 224bits |
| Packet size | 8000bits+192bits+224bits |

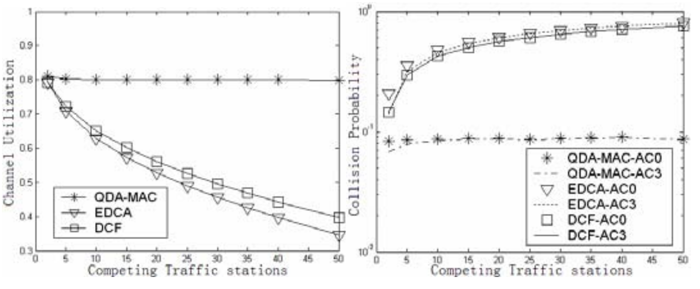
### 3.1 Evaluations under transient conditions

To verify the adaptive performance of the QDA-MAC scheme, AC3 and AC0 all starting with 10 stations in scenario 1, we have $N_3 = N_0 = 10$. Let 10 more AC3 stations join the network at 20s. Thus after 20s, AC3 increases to 20 stations and AC0 still is 10 stations in the network. Simulation finishes at 40s. We evaluate simulation results which report the change of total channel utilization and the impact of the $\alpha$ -value on the transient length. Simulation and numerical results given in the figure 5 (a) indicate that the proposed scheme is able to achieve a high average channel utilization 0.771, which is only 4% lower than theoretical maximum channel utilization 0.8011 before 20s. Figure 5(b) plots the simulated utilization ratio and it target value. As expected, the simulated ratio is kept tightly around the target value 2.0. At 20s, the network experiences a sudden change on the number of AC3 traffic. Both the channel utilization and utilization ratio can re-approach the desired levels after a short period in response to the charge of network condition by using the proposed adaptive scheme. After 20s, though the total utilization of AC3 increase due to the increment of the number of AC3 stations, the utilization ratio between a AC3 station and a AC0 station still is around the target value 2.0, as shown in figure 5 (b).

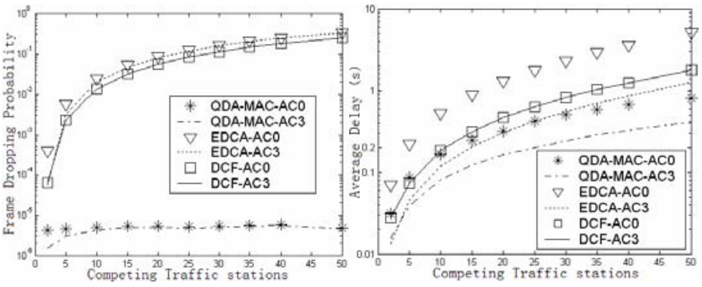
It is worth pointing out that the ( $N_3 p_3 + N_0 p_0$ ) value is almost constant if each traffic class is adopting optimal transmission probability. As a matter of fact, this is also be confirmed in Table 1. For this reason, we may use different $\alpha$ values to evaluate adaptive performance of the QDA-MAC scheme. Therefore, results in figure 5 (c) show that when the additional 10 AC3 stations join in the network, the ( $N_3 p_3 + N_0 p_0$ ) value sharply increase for beyond the optimal value. However, after a transient period the optimal ( $N_3 p_3 + N_0 p_0$ ) is reached again. The length of the transient period depends on the $\alpha$ parameter value. We can see from figure 5 (c) that $\alpha$ =0.9 is a good compromise between accuracy and promptness. For this reason, we use $\alpha$ =0.9 as the default value.

### 3.2 Evaluations under steady-state conditions

In scenario 2, the load is gradually increased in order to observe how the number of prioritized traffic stations impacts the performance of the proposed adaptive scheme. And one important point is noted. This point just is the performance of the QDA-MAC supporting QoS differentiation. The fixed package size for both traffic classes is 1000 bytes and the number of competing traffic stations is in the range [ $N_3 = N_0 = 2$ ,…, 50]. Under the same scenario configurations, We evaluate carefully channel utilization, collision probability, frame dropping probability and average MAC delay obtained via simulation for the proposed QDA-MAC, standard IEEE 802.11 DCF (CWmin(AC3)= CWmin(AC0)=32) and IEEE 802.11e EDCA (CWmin(AC3)= 16，CWmin(AC0)=64).



(a) Channel utilization (b) Collision probability

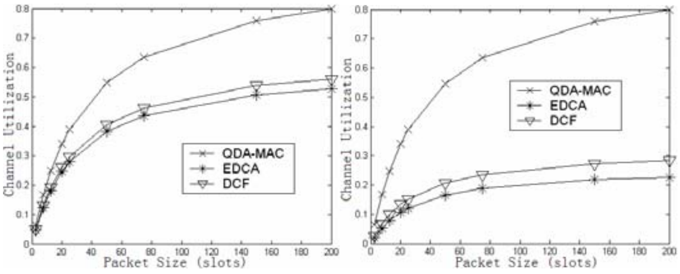


(c)Frame dropping probability (d) Average delay

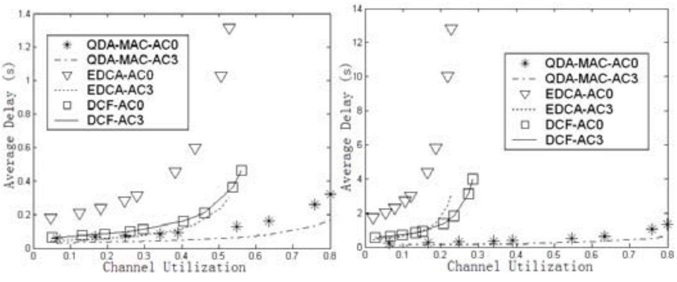
Figure 6 System performance vs. the number of traffic stations

The simulation results show that the QDA-MAC scheme is very effective. As shown in figure 6 (a), the channel utilization achieved by the QDA-MAC is almost independent of the number of competing traffic stations, whereas performance metrics of DCF and EDCA mechanisms decline significantly with the increment in traffic station number. Specifically, when we set average delay restriction of 200ms for the real-time traffic, the proposed QDA-MAC can access about 30 AC3 stations to support strict QoS in the network. However, supporting the same delay restriction, EDCA and DCF access only about 16 and 11 AC3 stations respectively, as seen in figure 6 (d). The performance of the QDA-MAC supporting strict QoS for real-time traffic is much better than that of the IEEE 802.11e EDCA. Therefore, simulation results indicate that the proposed adaptive scheme can not only provide QoS differentiation among multiple traffic classes but also still support strict QoS for real-time application.

In figure 6, we also observe that the collision probability of the QDA-MAC is almost independence of the number of competing traffic stations, whereas the average delay increases significantly with the increment in station number. This is due to the fact that in heavy load case, lower transmission probability of each traffic class can achieve better performance to maximize channel utilization in the proposed adaptive scheme. As a result, each packet suffers from long service time but still maintains low collision probability and frame dropping probability.



(a) Utilization( $N_3 = N_0 = 20$ ) (b) Utilization( $N_3 = N_0 = 80$ )



(c) Average delay( $N_3 = N_0 = 20$ ) (d) Average delay( $N_3 = N_0 = 80$ )

Figure 7 System performance with different packet lengths

In scenario 3, we use different number of prioritized traffic stations [20 ( $N_3 = N_0 = 20$ ), 80 ( $N_3 = N_0 = 80$ )] in a rectangular grid to evaluate the total channel utilization and average MAC delay for a wide set of packet lengths ranging from 2.5 (slots) to 200 (slots). From figure 7, we can find that the QDA-MAC scheme achieve much higher channel utilization and shorter average delay than standard DCF and EDCA mechanisms in all different configurations. In particular, figure 7 (c) and (d) plot the MAC delay vs. channel utilization for two traffic classes. Simulation results indicate that QDA-MAC is able to maintain very low MAC delay for AC3 and AC0 traffics even when it approaches the maximum channel utilization. By contrast, despite providing QoS differentiation, the EDCA behaves worse than the QDA-MAC under light and heavy load conditions.

From the above results, the QDA-MAC scheme is able to be feasible for a variety of WLAN environments to provide service differentiation and achieve maximum channel utilization. In addition, the low computational complexity makes our proposed adaptive scheme be suitable for real-time implementation.

Table 3 lists clearly the optimal initial window sizes of priority AC3 and AC0 classes with different packet length settings. These initial window sizes are analytically derived in the QDA-MAC scheme which exploits reasonably the relationship between the p-persistent model [7] and the Markov model [6] by mapping p-persistent transmission probabilities onto 802.11 MAC initial contention window sizes. This relationship is not reported here (More details see [16]) due to the space constraints. In other words, the proposed QDA-MAC scheme can be implemented in the original IEEE 802.11 with very little effort.

Table 3 Minimum contention window and utilization with different packet length settings

| length(slots) | 12.5 | 20 | 25 | 50 | 75 | 150 |
|---|---|---|---|---|---|---|
| CWmin(3) | 213.89 | 239.33 | 253.52 | 321.57 | 372.10 | 508.90 |
| CWmin(0) | 426.32 | 477.20 | 497.71 | 641.73 | 742.83 | 988.30 |
| $\rho_u$ | 0.2482 | 0.3411 | 0.3899 | 0.5478 | 0.6350 | 0.7593 |

## 4 Conclusions

In this paper, we have defined and evaluated a new scheme named QDA-MAC. This scheme has been designed to improve the channel utilization and achieve QoS provisioning for an IEEE 802.11 network by dynamically tuning its back-off algorithm. The most original aspect of our work is that QDA-MAC scheme only needs a very simple characterization of the network. As a result, our scheme does not need any estimate of the number of active stations for each class. We introduce a new parameter called persistent factor in the QDA-MAC scheme. Based on the different network conditions, the proposed scheme is able to timely adapt persistent factor to its optimal value in order to achieve maximum channel utilization. And then the transmission probability of each priority class can be updated by optimal persistent factor. Accordingly, the proposed scheme can fine tune the network to optimal working state in a dynamic environment. Simulation of three scenarios has been used for investigating the proposed scheme performance both in transient and steady-state conditions. The simulation results demonstrate the satisfactory performance of the proposed adaptive MAC scheme. In addition, the low computational complexity makes our proposed scheme feasible for all different WLAN environments.

The future work of this paper will continue to improve the algorithm so that it can be feasible for different traffic conditions, such as non-saturation condition, variant rate traffic flow. And the impact of hidden terminals on the proposed scheme will be analyzed in the near future.

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