Multi-Class QoS in 802.11 Networks using Gentle Decrease of Multiple Contention Windows

Bushra Anjum and Zartash Afzal Uzmi
Computer Science and Engineering
Lahore University of Management Sciences, Lahore, Pakistan
Email: {bushraa,zartash}@lums.edu.pk

***Abstract*—IEEE 802.11 Distributed Coordination Function (DCF) uses a binary exponential backoff algorithm to arbitrate simultaneous channel access by multiple stations. When a station senses that either the shared wireless channel is busy or a collision has occurred, that station must delay the transmission by backoff time. This backoff time, in legacy DCF, is uniformly selected from a common contention window range that, in turn, ensures equal chance of grabbing the wireless medium by each station. Therefore, legacy DCF does not support service differentiation or priority access to the channel. To support service differentiation and increased Quality of Service (QoS), we propose two enhancements to the procedures used for managing contention window in original protocol. These two enhancements can be easily incorporated within the legacy DCF mechanism.**

First, instead of a common window for all classes, each traffic class is assigned a contention window with minimum and maximum values which are specific to that class. Second, the backoff algorithm is adjusted to follow a Multiple Increase Multiple Decrease (MIMD) procedure. First enhancement provides service differentiation and the second improves performance for all traffic classes. Unlike previous schemes, our proposed scheme does not require protocol changes in the legacy DCF. We evaluate our scheme using extensive simulations and demonstrate that, in comparison with legacy DCF, our newly proposed scheme provides a throughput increase of about 30% for high priority flows and of about 20% for medium priority flows.

I. Introduction

The desire to combine data connectivity with user mobility has resulted in a growing use of wireless local area networks (WLANs). The deployment of wireless LANs is accelerated by ease of installation, flexibility, and availability of low-cost devices. Most notebooks shipped these days are equipped with wireless LAN capability and a large number of public places, university campuses, and company offices have WLAN access points installed, through which these notebooks can access the Internet. The first WLAN standard was endorsed by the IEEE 802.11 Committee in 1997 [1]. Today, most WLAN products are based on versions of IEEE 802.11 standard which defines medium access control (MAC) and physical layer protocols for communication in a wireless local area environment.

While the WLAN deployments have seen a tremendous growth, network traffic has also evolved to represent a multitude of classes, where each class expects a different level of service from the network. Furthermore, emergence of mission-critical and other multimedia applications, such as VoIP and video conferencing, has created traffic classes with stringent real-time QoS requirements. For these emerging applications, the capability to provide multi-class Quality of Service (QoS) has become a need rather than a feature. Therefore, it is expected that a network, whether wired or wireless, is able to provide service differentiation to multi-class traffic, while meeting strict QoS constraints. In this paper, we address the problem of service differentiation and QoS in IEEE 802.11 based wireless networks.

Most wireless local area networks deployed today are based on IEEE 802.11 standard which specifies the use of a shared physical medium, also called the wireless channel. It is thus required to use some multiple access mechanism to transmit and receive data on this shared medium. The basic multiple access mechanism employed by IEEE 802.11 standard is called the Distributed Coordination Function (DCF). The underlying principle of DCF is carrier sense multiple access (CSMA) where a station senses the medium before transmitting. If the medium is found idle, the station may transmit, otherwise it refrains till the end of current transmission. For many existing applications, the DCF mechanism exhibits an acceptable performance. However, DCF, in its legacy form, is unable to cater to applications that require priority service and time-bounded transfer of data.

To support applications that require time-bounded transfer of data, the IEEE 802.11 included an extension of DCF called the Point Coordination Function (PCF). The PCF mechanism maintains a list of all those stations which have time sensitive data to transmit, and special timely opportunity is given to each station for transmission. This opportunity is given by a poll message and is governed by a single central station. Although PCF was designed to support multi-class traffic with QoS requirements, the centrally controlled polling mechanism inherent in PCF causes inefficiencies due to which it is rarely implemented by WLAN equipment vendors [2]. However, the need for multi-class QoS is ever increasing and has, thus, motivated current research activities to enhance the 802.11 multiple access mechanism [3]–[9].

Most of the work done in multi-class QoS provisioning tries to solve this problem by proposing enhancement to the conventional contention window (CW) scheme of 802.11 DCF [6]–[9]. The contention window represents a range from which a backoff time is uniformly selected, where the backoff time is the amount of time by which a station must delay its transmission, in case that station senses a collision or a busy medium. In traditional mechanism, an unsuccessful attempt to transmit a packet of data increases, usually doubles, the contention window while a successful transmission immediately resets the contention window. We propose enhancing the contention window scheme used in DCF by judiciously combining two independent observations: 1) Allowing different CW ranges for different classes provides service differentiation [9], and 2) After a successful transmission, a sequential decrease of CW rather than resetting it to an initial value, as in legacy DCF, improves the throughput performance [3], [4].

Our goal is to provide a multi-class QoS support mechanism, in 802.11 MAC protocol, that achieves high wireless link utilization, without requiring a revamp of the legacy DCF. Our new scheme, Gentle Decrease with Multiple Contention windows (GDMC), combines the above two observations: it uses different contention window (CW) ranges for different traffic classes and, after a successful transmission, it causes a gentle decrease of contention window. This mechanism obviates the need to maintain network history as was required by schemes proposed in [5] and [9]. This not only leads to a simpler implementation but also allows the nodes to stop monitoring the channel continuously, resulting in energy savings and an extension in battery life.

In our proposed scheme, provision of different contention window (CW) ranges for different traffic classes means that a traffic class can choose its backoff time from a range which is independent of the range of backoff time for any other traffic class, thus selecting the privilege level that is independent of other classes. The GDMC scheme, at one hand, provides separate CW ranges for strict service differentiation and, at the other hand, can allow overlap of these ranges to increase network utilization under relaxed network conditions. With independent CW ranges for each traffic class, the GDMC scheme offers as high as 30% increased throughput as compared to legacy DCF for the high priority flows. The medium priority flows get a throughput increase of as high as 20%. This strict differentiation, however, may bring about a drop of about 10% in throughput of background traffic. These ratios are tuneable with the adjustment of overlap between the CW ranges.

The rest of the paper is organized as follows: Section II covers background material including a brief description of 802.11 DCF mechanism. Section III covers some of the existing schemes proposed for 802.11 enhancements for support of multi-class traffic. Section IV describes our proposed GDMC scheme, followed by a comparative simulation study in Section V. We finally conclude in Section VI.

II. Background

The IEEE 802.11 proposes two mechanisms for accessing wireless medium. The first one is distributed in nature and is called Distributed Coordination Function (DCF). The other mechanism is centralized and is known as Point Coordination Function (PCF). In 802.11, DCF is mandatory while PCF is optional; most WLAN vendors do not provide an implementation of PCF in their devices for reasons of inefficiency associated with a centralized polling mechanism used by PCF [2]. More complex coordination functions have been defined by enhancing the original DCF and PCF, and incorporated in the 802.11e standard. In our scheme, we study the extent of service differentiation that can be provided without sacrificing the simplicity of DCF. In the following, we provide a brief overview of DCF mechanism and the corresponding binary backoff algorithm.

DCF is the basic channel access mechanism for IEEE 802.11, and employs a Carrier Sense Multiple Access (CSMA) with Collision Avoidance (CA) algorithm to manage access to the shared medium. When a station has a packet to transmit, it senses the carrier to determine whether the wireless medium is busy or idle. If the medium is found idle, the station waits for a small duration of time, known as DCF Inter Frame Space (DIFS). If the medium still remains idle during DIFS, the station transmits the frame. If the medium is initially busy or it becomes busy during DIFS, the station defers the transmission by entering into a wait period called backoff time. The backoff time is determined by the binary exponential backoff algorithm described below.

Each station stores a local variable CW, short for contention window. The initial value of CW is taken as $CW_{\min}$ (31 in legacy DCF). Whenever a station needs to backoff, it generates a random number, the backoff time, uniformly from the interval $[0, CW]$, also referred to as CW range. A backoff timer starting from the generated value of the backoff time is decremented by one for each time slot the medium remains idle. This process continues until either the medium becomes busy again or the backoff timer becomes zero, at which point the station is allowed to transmit if the channel is sensed idle for one DIFS. With every deferred transmission attempt, CW doubles[1], until a maximum value $CW_{\max}$ is reached (1023 in legacy DCF). If, however, a transmission attempt is successful, CW is immediately reduced to $CW_{\min}$ for the next transmission attempt. If i denotes the number of successive failed attempts to transmit (due to collision or sensing of busy medium), the contention window algorithm explained above can be summarized in the following equations:

$$CW_i = \begin{cases} CW_{\min} & i = 0 \\ \min(2(CW_{i-1}+1)-1, CW_{\max}) & else \end{cases}$$

$$\text{Backoff Time} = Unif.Rand([0, CW_i])$$

Carrier sensing in 802.11 is done at two levels: virtual and physical. The Physical carrier sense mechanism is provided by the physical layer and declares the channel as busy if there is physical presence of signal on the radio medium. The Virtual carrier sense mechanism, on the other hand, is provided by the MAC layer and uses the prediction of signal on the radio medium to proclaim channel as busy. This virtual mechanism uses a local register called Network Allocation Vector (NAV) which maintains a prediction of future traffic on the medium based on the duration information that is announced by other stations in short control frames prior to their actual exchange of data. It is to be emphasized that if the NAV of a station

[1] It is, in fact, the value $CW+1$ which doubles on a deferred transmission attempt but it is common practice to say that contention window doubles.

indicates that the medium is busy, the medium is considered busy whether or not it is physically carrying a transmission.

III. Existing Schemes

First, we mention the general approaches taken by the researchers to incorporate multi-class QoS in 802.11 networks. This is followed by a brief description of three schemes, each of which is a representative of the class of schemes that use one or more of the general approaches.

A. General approaches

Proposed improvements to DCF are variations of one or more of the following three approaches [3]–[9]:

1) Using network history to better utilize network resources
2) Enhancements to the conventional procedure for adjustment of the contention window
3) Contention Window Range based Differentiation

In the last approach above, each traffic class has its own set of CW parameters $(CW_{\min}, CW_{\max})$ and generates independent backoff values. Thus a single station maintains several backoff time values, one for each traffic class. The prioritized channel access is realized as follows. A high priority traffic class has small values of $CW_{\min}$ and $CW_{\max}$, whereas a low priority traffic class has larger values of these parameters. As a result, a high priority traffic class is likely to choose a smaller value of backoff time than a low priority one which, in turn, means that a high priority traffic class will get hold of channel sooner than the low priority one. Thus, separate values of CW parameters for each class lead to service differentiation.

B. Predictive DCF [5]

Predictive-DCF allows each node to choose its next backoff time based on the network history, where *history* could be as simple as the number of idle slots between adjacent successful transmissions on the network. This provides an idea of network load and thus can be used to adjust a backoff interval to avoid further collisions. Predictive DCF improves performance only when the number of competing nodes is small (less than 10). Furthermore, there is no direct support for service differentiation.

C. Sliding Contention Window (SCW) [9]

Sliding Contention Window (SCW) controls the backoff values of different traffic classes by providing separate CW ranges of each traffic class. Moreover, an overlap between CW ranges of different traffic classes is also permitted in order to achieve high medium exploitation in relaxed network conditions. The SCW scheme associates with each traffic class c a sliding contention window $SCW[c]$ defined by a lower bound $CW_{c,\text{LB}}$ and an upper bound $CW_{c,\text{UB}}$. These bounds delimit the interval from which the flows of traffic class c randomly select the backoff value. The values $CW_{c,\text{LB}}$ and $CW_{c,\text{UB}}$ are adjusted dynamically, by means of a parameter called sliding factor, using the network history of failed transmission attempts and dropped packets. The history parameters are Medium Occupancy Ratio $B(T)$ for background traffic and Loss Ratio α for all other traffic classes.

D. Gentle DCF/Probabilistic DCF [3], [4]

Gentle DCF (GDCF) is based on the observation that 802.11 DCF increases its CW exponentially with each deferred transmission attempt, but resets the CW to the initial value after each successful transmission. This is based on the assumption that each successful transmission is an indication that the system is under low traffic load. GDCF proposes a change in the conventional strategy and takes a more conservative measure by halving the contention window size after c consecutive successful transmissions, i.e., it uses a multiplicative increase multiplicative decrease (MIMD) strategy. Probabilistic DCF (by the same group of authors) also follows the same logic but includes a probability factor in halving the contention window, i.e., it halves the contention window with a probability f after each successful transmission.

IV. The Proposed GDMC Scheme

History based protocols are more suited to a wired environment; the primary reason is that wireless networks may experience a condition called handoff in which mobility causes a disconnection from one WLAN and reconnection to another one. Thus, after each handoff, a station is required to wait for some time to gather enough history information to make decisions about how to use the channel most effectively. More importantly, history requires maintenance of certain parameters that are foreign to 802.11 MAC, such as Loss Ratio α and Medium Occupancy Ratio $B(T)$, as given in [9]. Computation of these history parameters requires continuous observation of the channel which completely omits the use of NAV, thus bypassing the virtual carrier sense mechanism. Thus, existing history-based schemes, such as the one given in [9], suffer from two problems: 1) they do not make use of NAV, requiring continuous monitoring of the channel, resulting in power inefficiency, and 2) they maintain history using parameters that are foreign to 802.11 MAC, requiring a change in the legacy DCF mechanism. Despite these two shortcomings, SCW and similar schemes that use sliding contention windows promise service differentiation and thus offer an attractive strategy to support multi-class QoS.

Thus, our first observation is that any new scheme that aims to support multi-class traffic should provide different contention windows but the contention windows should be adjusted without using additional parameters for maintaining network history. Our second observation, also noted in [3] and [4], is that if the current value of CW, say CW_{cur}, is at some large value, some collisions must have occurred recently, alluding to heavy traffic. Thus, we may gather history information from CW_{cur} without continuously monitoring the channel. It also follows that a high value of CW, which indicates recent collisions, should not be decremented to $CW_{\min}$ immediately, otherwise more collisions will be likely. Thus, the variable CW should be decreased gently. These observations lead to our proposed scheme: Gentle Decrease of Multiple Contention Windows (GDMC).

We believe that the basic idea of range based differentiation, without introducing any new parameters, is strong enough to support both service differentiation and dynamic tuning of this differentiation, and also feasible to be incorporated in the existing standard 802.11. Furthermore, within each traffic class, the MIMD procedure for adjusting CW can further enhance its throughput performance.

In our proposed scheme, each traffic class c has its own copy of $CW_{\min,c}$, $CW_{\max,c}$ and $CW_{cur,c}$ parameters (as in [9]). For each traffic class, the backoff time is uniformly chosen from the interval $[CW_{\min,c}, CW_{cur,c}]$. The parameters $CW_{\min,c}$ and $CW_{\max,c}$ are assigned values by higher layers to support strict or relative service differentiation. The variable $CW_{cur,c}$ follows the same exponential increase procedure as of original DCF. However, it now also follows a step by step decrease by halving the value on each successful transmission (similar to that in [3], [4]), instead of suddenly resetting it to $CW_{\min,c}$.

If $CW_{cur,c}$ denotes the current value of contention window variable, and I is an indicator variable if preceding transmission was deferred (due to collision or sensing of busy medium; $I = 0$ means successful transmission), and c denotes a particular traffic class, the GDMC scheme can be summarized in the following equations:

$$CW_{cur,c} = \begin{cases} \max\left(\frac{CW_{cur,c}+1}{2} - 1, CW_{\min,c}\right) & I = 0 \\ \min(2(CW_{i-1}+1) - 1, CW_{\max,c}) & I = 1 \end{cases}$$

$$\text{Backoff Time} = Unif.Rand([CW_{\min,c}, CW_{cur,c}])$$

In summary, our proposed GDMC scheme uses the following procedures:

1) It uses range based service differentiation by keeping individual copies of $CW_{\min,c}$ and $CW_{\max,c}$, as dictated by higher layers, for each traffic class c.
2) It uses MIMD procedure for adjustment of $CW_{cur,c}$ variable for each traffic class c.
3) It does not require any additional parameters to maintain network history (such as α and $B(T)$ in [9]), and does not forgo the NAV-based virtual carrier sense mechanism of legacy DCF. Thus, there is no need to continuously sense the channel, leading to extended battery life.

This guarantees a multi-class support (due to range based differentiation) with enhanced throughput (due to MIMD mechanism), without revamping the existing DCF mechanism.

V. Comparative Performance

This section presents a simulation analysis of proposed enhancements and modifications to the DCF, including our new GDMC scheme, comparing the performance of these schemes with those of legacy DCF. We first describe the model and specifications used for the simulation study.

A. Simulation Environment and Scenarios

All simulations are done using OMNeT++ simulator and its mobility framework. Our simulation model consists of a 2 Mbit/s wireless LAN in the BSS mode [1], consisting of various wireless stations communicating with a base station (or access point AP), which is connected to the wired network. This base station acts as sink during uplink and both as source and sink during two-way traffic (while modeling audio/video conferencing). As all the communication in an IEEE 802.11 network in infrastructure mode is conducted through the base station, the results of communication with the access point (AP) are similar to those of stations communicating with each other. The access mechanism we consider is a four way handshaking protocol by using the RTS/CTS/DATA/ACK dialogue [1], as specified by IEEE 802.11 infrastructure mode with distributed coordination function (DCF). Thus, the hidden node problem does not arise. We also assume that the nodes are not mobile during the simulation period.

In our simulations, each wireless node generates a different flow representing one of the three uniquely prioritized traffic classes: high priority (HP), medium priority (MP) and best effort (LP). We use constant bit rate (CBR) sources to emulate multimedia and best effort traffic. Table I shows the simulation environment specifications and Table II shows the parameters used for SCW scheme.

TABLE I
Simulation Network Specifications (OMNET++)

Parameter	Value
High priority payload	160 bytes
Medium priority payload	800 bytes
Low priority payload	1500 byte
PHY Header	24 bytes
MAC Header	37 bytes
MAC Queue Size	100 packets
RTS	20 bytes
CTS	14 bytes
ACK	14 bytes
Channel bit rate	2 Mbps
SIFS	10μs
DIFS	2λ + SIFS
Time slot duration (λ)	20μs
Number of High priority nodes	10
Number of Medium priority nodes	15
Number of Low priority nodes	15

B. Simulation Results

We now present simulation results that compare the throughput performance of the GDMC scheme with legacy DCF and with the three schemes described earlier. We report comparative performances for background, medium and high priority traffic classes in separate graphs. Before discussion of results and inferences made therefrom, it may be noted that:

1) The legacy DCF in 802.11 and Predictive DCF do not support service differentiation, and exhibit the same performance across all traffic classes.
2) Since the number of nodes in our simulations was at least 10, Predictive DCF never outperformed the legacy DCF (for reasons explained in section III-B).

TABLE II
PARAMETERS USED FOR SCW SCHEME

Parameter	Value
Sliding factor (High priority)	16
Sliding factor (Medium priority)	32
Sliding factor (Low priority)	128
Sliding CW size (High priority)	32
Sliding CW size (Medium priority)	64
Sliding CW size (Low priority)	256
$[CW_{\min}, CW_{\max}]$ (High priority)	[0, 256]
$[CW_{\min}, CW_{\max}]$ (Medium priority)	[32, 512]
$[CW_{\min}, CW_{\max}]$ (Low priority)	[128, 1024]

3) The starting portions of all the graphs indicate a transient behavior which we have chosen to include for illustration purposes.
4) In all throughput comparison graphs, the vertical axis represents the 'Throughput Ratio' which is the ratio of successfully delivered packets to transmitted packets, while the horizontal axis of all graphs represents the 'Simulation Time' in seconds.

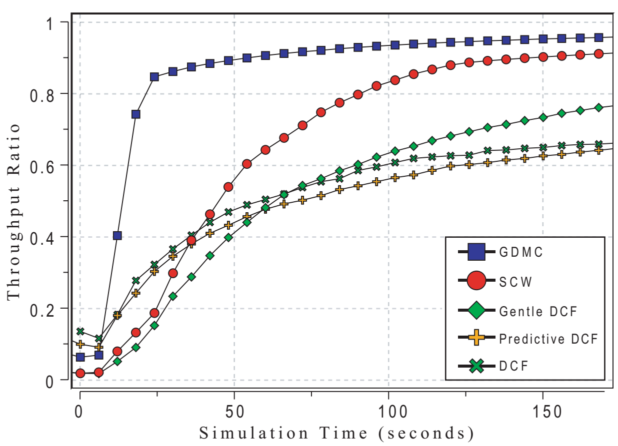

Fig. 1. Throughput Comparison for High Priority Traffic.

Figure 1 depicts the throughput performance of high priority traffic under various schemes. The GDCF scheme shows a 15% throughput increase over DCF, replicating the results reported in [3]. The SCW scheme, due to its separate contention windows for different traffic classes, performs much better, yielding 25% increased throughput over legacy DCF. Our proposed scheme GDMC performs still better and provides about 30% throughput increase. This additional increase in throughput, as compared to SCW, is possible because the wait times required to gather channel history (required for α and $B(T)$) are eliminated in GDMC. Moreover, the MIMD procedure used in GDMC for each traffic class further boosts the throughput performance of that traffic class.

Figure 2 shows the throughput comparison for medium priority traffic. As with the high priority traffic, GDMC maintains the 5% performance margin over SCW. The throughput ratio exhibited by GDCF remains almost the same as in case of high

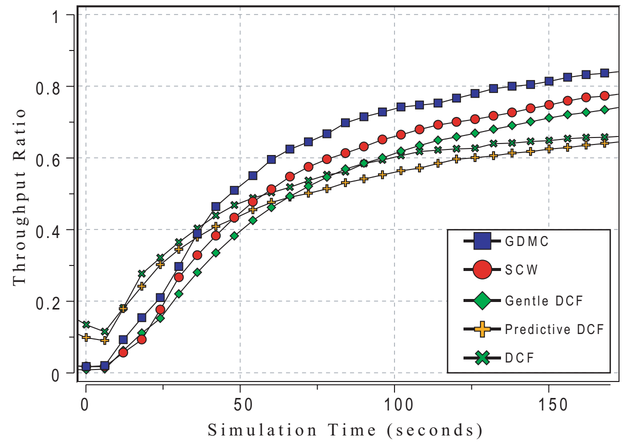

Fig. 2. Throughput Comparison for Medium Priority Traffic.

priority flows. Legacy DCF and Predictive DCF lack traffic class differentiation, and, therefore, exhibit exactly the same performance as is observed in case of high priority traffic.

For background or lowest priority traffic, DCF exhibits the highest throughput among all the schemes, as depicted in figure 3. This is quite expected because DCF (also Predictive DCF) provides equal opportunity to all traffic classes, whereas the other schemes grant reduced opportunity to background traffic in order to provide higher throughput for higher priority classes. For background traffic, SCW suffers the most decrease in throughput. This is because in SCW, the background traffic, unlike the higher priority traffic, always gets strictly residual bandwidth, governed by the Medium Occupancy Ratio $B(T)$, regardless of the level of contention. In contrast, GDMC uses the MIMD procedure for CW adjustment for all traffic classes, resulting in a moderate performance hit for background traffic.

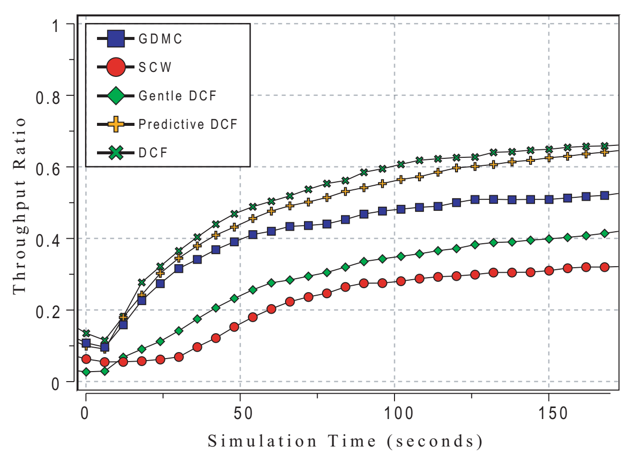

Fig. 3. Throughput Comparison for Low Priority Traffic.

Figure 4 compares the delay characteristics of high priority traffic, depicting that DCF and Predictive DCF exhibit almost the same performance. GDCF exhibits a lower average delay since the number of collisions are reduced by the use of MIMD procedure. SCW further reduces the average delay since it assigns a smaller contention window to high priority traffic.

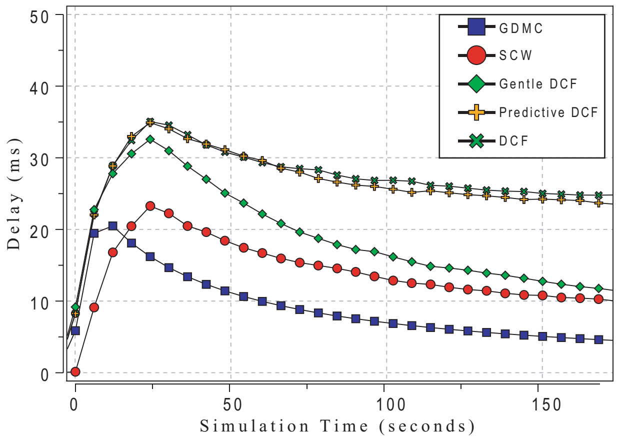

Fig. 4. Average End-to-End Delay for High Priority Traffic.

The GDMC scheme shows a further reduction in average delay since, unlike SCW, it does not spend any time for collecting the network history.

We also evaluate the ability of GDMC to provide service differentiation, as the network load is increased. We use four traffic classes and allocate them different contention windows, as given in Table III. Throughput results shown in figure 5 are obtained by gradually increasing the network load; after every 5 seconds of simulation time, we add 4 new CBR flows, one from each of the four traffic classes. We notice that the throughput for each class increases with the network load until the network becomes saturated at about 112 flows (28 flows for each traffic class). Any further increase in network load results in a drop in throughput for each traffic class. As figure 5 indicates, high priority flows experience the largest drop in throughput. This is because the high priority flows have relatively smaller contention window ranges, while the increase in load for all traffic classes is similar (one new flow every five seconds of simulation time).

TABLE III
GDMC: Contention Windows for Different Classes

Traffic Class	$CW_{\min}$	$CW_{\max}$
Class 1 (Highest priority)	0	64
Class 2	64	256
Class 3	128	512
Class 4 (Lowest priority)	512	1024

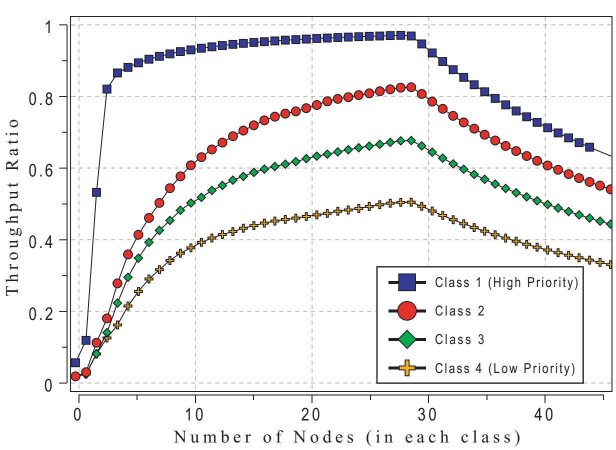

Fig. 5. GDMC Service Differentiation with Increasing Network Load.

From figure 5, we also observe that GDMC may support more traffic classes compared to the schemes of [3] and [4] which do not show any visible service differentiation beyond three traffic classes. This is because both these schemes use a new additional parameter (c in [3] and f in [4]) for each traffic class. The range of values of these new parameters (1-4 for c and 0.2-0.4 for f) restricts the total number of distinct traffic classes that can be supported. We found through simulations that the schemes in [3] and [4] can practically support at most 3 different traffic classes. In contrast, as shown in figure 5, the GDMC scheme can support service differentiation for an increased number of service classes.

VI. Conclusions

We proposed GDMC, a new scheme for service differentiation in 802.11 WLANs. GDMC uses independent contention windows for each traffic class and an MIMD procedure to adjust the contention window for a particular class. Using this scheme, we observed about 30% improved throughput for high priority flows and about 20% increased throughput for medium priority flows when compared with legacy DCF. Furthermore, the GDMC scheme operates under standard procedures of 802.11 DCF, is scalable to a large number of competing nodes, and can support many distinct traffic classes compared to previously proposed schemes.

References

[1] LAN/MAN Standards Committee of the IEEE Computer Society, "Wireless LAN medium access control (MAC) and physical layer (PHY) specification," IEEE Std 802.11-1997 edition, 1999.

[2] S. Choi, "Emerging IEEE 802.11e WLAN for Quality-of-Service (QoS) Provisioning," *SK Telecom Telecommun. Rev.*, vol. 12, no. 6, pp. 894–906, 2002.

[3] C. Wang, B. Li, and L. Li, "A New Collision Resolution Mechanism to Enhance the Performance of IEEE 802.11 DCF," *IEEE Transactions on Vehicular Technology*, vol. 53, no. 4, pp. 1235–1246, July 2004.

[4] C. Wang and W. Tang, "A Probability-based Algorithm to Adjust Contention Window in IEEE 802.11 DCF," in *Proceedings of ICCCAS*, June 2004.

[5] N. Choi, Y. Seok, Y. Choi, S. Kim, and H. Jung, "P-DCF: Enhanced Backoff Scheme for the IEEE 802.11 DCF," in *Proceedings of the 2005 IEEE VTC-Spring*, May 2005, pp. 2067–2070.

[6] N.-O. Song, B.-J. Kwak, J. Song, and L. E. Miller, "Enhancement of IEEE 802.11 Distributed Coordination Function with Exponential Increase Exponential Decrease Backoff Algorithm," in *Proceedings of the 2003 IEEE VTC-Spring*, New Orleans, April 2003.

[7] W. Kuo and C.-C. J. Kuo, "Enhanced backoff scheme in CSMA/CA for IEEE 802.11," in *Proceedings of the 2003 IEEE VTC-Fall*, Orlando, October 2003, pp. 2809–2813.

[8] J. Deng, P. K. Varshney, and Z. J. Haas, "A New Backoff Algorithm for the IEEE 802.11 Distributed Coordination Function," in *Proceedings of the Communication Networks and Distributed Systems Modeling and Simulation (CNDS)*, San Diego, January 2004.

[9] A. Nafaa, A. Ksentini, and A. Mehaoua, "SCW: Sliding Contention Window For Efficient Service Differentiation in IEEE 802.11 Networks," in *Proceedings of the 2005 IEEE Wireless Communications and Networking Conference (WCNC)*, France, March 2005, pp. 1626–1631.