A QoS-Based MAC Protocol for Ad Hoc WLANs

Farshad Eshghi, **Member, IEEE**, and Vikram Krishnamurthy, **Fellow, IEEE**
Dept. of Electrical and Computer Engineering, University of British Columbia, Vancouver, BC, Canada
farshade,vikramk@ece.ubc.ca

**Abstract**—Differentiated services provision is essential for satisfactory performance of ad hoc wireless local area networks (WLAN) carrying applications with different requirements. The IEEE 802.11 protocol, as the dominating standard, does not support differentiated services in its original ad hoc mode of operation, distributed coordination function (DCF). In this paper, a new access protocol is proposed which seamlessly sits on top of and is completely compatible with the IEEE 802.11's DCF and point coordination function (PCF). The new access protocol can successfully prioritize the traffic according to a pre-defined cost function using a burst of black slots. Performance analysis together with comprehensive simulation studies show improved performance, fairness, and differentiation capability over IEEE 802.11.

I. **INTRODUCTION**

As the communications needs shift from data-only toward triplay (data, voice, and video), networks are required to maintain different levels of quality of service (QoS) depending on the nature of the subject application. The QoS implementation spans multiple layers of the layered stack network model. However, as far as ad hoc WLANs are concerned, which is our focus in this paper, the bottleneck and the most challenging layer for QoS implementation is the medium access control (MAC) layer. This is due to the lack of any centralized control as opposed to infrastructured WLANs. The QoS implementation at MAC layer is simply translated to priority accommodation. Among the introduced WLAN standards, due to its compatibility with IEEE 802 protocol suite, IEEE 802.11 has become the dominating standard. In the ad hoc mode of operation, IEEE 802.11’s distributed coordination function (DCF) is based on best-effort and does not support differentiated services.

A. **Main Results**

In this paper, we propose a new distributed access protocol, **Priority-Grouped Distributed Medium Access (PGDMA)**, whereby all nodes schedule their transmissions in a TDMA fashion following a scheduling phase. The new protocol has several properties that are essential for efficient implementation of ad hoc WLANs. These include:

- **The proposed PGDMA protocol imposes no restriction on the nodes’ channel access instants.**
- **It sits suitably on top of and is completely compatible with the IEEE 802.11’s DCF and point coordination function (PCF).**
- **To implement scheduling in PGDMA there is no need for information exchange amongst nodes, apart from transmission of a burst of black slots and minimal processing afterwards.**
- **Scheduling of nodes/packets is done according to a cost function which can accommodate a variety of criteria such as delay, application class, service priority (intrinsically or acquired e.g. financially), residual time-to-live constraint, etc.**
- **It guarantees time-bounded channel access as long as the protocol’s capacity limit is not violated.**
- **The proposed PGDMA protocol, which is basically an inter-node priority implementation, can also be combined with other intra-node prioritization technique as long as it is equally and simultaneously implemented at all nodes. Examples include different packet-scheduling algorithms [1].**

A mathematical model is presented for the proposed PGDMA protocol whereby its parameters are optimized. A detailed simulation study of the PGDMA protocol as well as IEEE 802.11’s DCF are also presented. Our simulation studies show that the simulated performance of the PGDMA protocol can be accurately predicted by our analysis up to the close-to-capacity node populations. Moreover, the simulation results show that the PGDMA protocol, despite of its extra bandwidth consumption for scheduling, outperforms the IEEE 802.11’s DCF in terms of measures of performance (MoP) of interest.

B. **Background**

Coordination between nodes is essential in the realization of distributed priority. To overcome the inherent bandwidth cost of such coordination, the volume of information exchange should be kept as low as possible. A novel approach was introduced in [2] and [3]. This new access technique overlays IEEE 802.11’s DCF: real-time traffic uses a shorter access IFS while data traffic accesses the channel according to DCF mode of operation. The real-time node schedules its transmission at specific instants each $t_{sch}$ apart. If after $t_{sch}$ the channel is perceived to be idle, the node transmits and if not, waits till the channel becomes idle and then enters a black-burst contention period. At this time, the node jams the channel with a number of black slots (pulses of energy of pre-specified duration). This number is proportional to the time that the node has been waiting for the channel to become idle since passing its scheduled access instant. The node with longest black-burst has the priority to transmit and all others will repeat the procedure. By adopting shorter access IFS, this technique guarantees higher priority of real-time traffic over data traffic. Moreover, by employing the black bursts, delay-based prioritization is implemented among real-time nodes. The basic assumption that all nodes
have equal inter-scheduled-transmission instants of \( t_{\text{sch}} \) is a very limiting one. Besides, there will be at least (in case of success) one black burst period per packet transmission.

The paper is organized as follows. Section II describes the new PGDMA protocol. Section III provides a state-space model of the system. This model allows us to optimize the protocol parameters. Section III concludes with a stability analysis of the protocol. Section IV presents extensive numerical examples of the protocol performance against the standard IEEE 802.11 on a realistic simulation testbed. We also show that the protocol analysis in Sec. III accurately predicts the protocol performance.

II. THE PRIORITY-GROUPED DISTRIBUTED MEDIUM ACCESS (PGDMA) PROTOCOL

The rationale behind the PGDMA protocol proposed in this paper is to let the nodes of the ad hoc WLAN compete for the channel in different classes, according to a pre-defined cost function, rather than in a single class. This will increase the probability of successful packet delivery and fairness, and facilitates priority accommodation.

In this section we present a detailed description of our proposed PGDMA protocol.

A. Notation and Terminology

The PGDMA protocol proposed in this paper employs the terminology defined below which will be used subsequently when describing the protocol. Most of the notation is illustrated in Fig. 1.

- **PGDMA cycle**: Intervals of time \( (T_P \text{ seconds}) \) within which the PGDMA protocol is implemented. This cycle is automatically initiated following an idle-channel with specific duration.
- **Scheduling phase**: Part of the PGDMA cycle during which nodes jam the channel in order to schedule their transmissions \( (T_{\text{SCHP}} \text{ seconds}) \).
- **Transmission (TX) phase**: Part of the PGDMA cycle during which nodes start their transmissions based on the scheduling-phase’s results \( (T_{TXP} \text{ seconds}) \).
- **Non-prioritized traffic, NPT**: The traffic that is transmitted based on best effort.
- **Prioritized traffic, PT**: The traffic that is assigned a priority class according to a pre-defined cost function.
- **Black slot**: A pulse of energy with pre-specified width of \( \Delta \) seconds [2]. Note that the scheduling phase is slotted by units of black slots.
- **Slot**: Time unit of \( \delta \) seconds which slots the transmission phase, and is equivalent to the IEEE 802.11’s slot.
- **Class counter, CC**: A counter that keeps track of node/packet’s scheduled priority class.
- **Slot counter, SC**: A counter that keeps track of a node/packet’s scheduled slot.
- **Class window size, \( n \)**: The number of slots in each priority class.
- **Cost function, \( W(\cdot) \)**: Determines a node/packet’s accrued cost function up to the beginning of a PGDMA cycle.
- **Black-slot burst length, \( \beta \)**: A node’s jamming period in terms of black slots.
- **Cost quantization-step, \( q \)**: The cost interval of a single priority class.
- **New inter-frame space, NIFS**: The new defined inter-frame space, following an idle-channel period of which a new PGDMA cycle is initiated \( (T_{\text{NIFS}} \text{ seconds}) \).

B. Protocol Description

In this section a description of the PGDMA protocol is presented.

In our proposed access scheme, NPT is treated according to the IEEE 802.11’s DCF mode of operation. That is, after sensing the channel idle for \( T_{\text{DIFS}} \text{ seconds} \), a node with the lowest randomly-selected slot number starts transmitting with or without using RTS/CTS dialogue. Regarding the PT, the channel time is divided into the new protocol implementation cycles called the PGDMA cycle. We start with the basic assumption of no-hidden terminals. Any PT-carrying node \( j \), \( j \in \{1, 2, \ldots, N\} \), with a ready-to-be-sent packet, following an idle-channel interval of \( T_{\text{NIFS}} \text{ seconds} \), jams the channel with an integer number, \( \beta(j, k) \), of black slots. The jamming period, during which transmission scheduling takes place, is called the scheduling phase. Parameter \( k \) denotes the PGDMA-cycle index. Denoting the cost quantization-step with \( q \), the black-slot burst length, \( \beta(j, k) \), is proportional to the node \( j \)’s cost accrued up to the beginning of the scheduling phase:

\[
\beta(j, k) = \left[ \frac{W(\cdot; j, k)}{q} \right] \quad \text{(1)}
\]

where \( W(\cdot; j, k) \) denotes the node \( j \)’s accrued cost function of possibly multitude of variables up to the beginning of the \( k^{th} \) PGDMA cycle. As a result, packets with higher costs assume longer jamming periods, and it is apparent that the scheduling phase time length is:

\[
T_{\text{SCHP}}(k) = \left[ \max_j \beta(j, k) \right] \Delta \quad \text{(2)}
\]
Beside counters present in the IEEE 802.11, there are two more counters provisioned in the PGDMA protocol, slot counter (SC) and class counter (CC), which implement transmission scheduling. For the sake of compatibility, the time slot duration of the SC can be set equal to the 802.11’s, herein denoted by $\delta$. Upon finishing its $\beta(j,k)$-black-slot burst transmission (jamming), each node listens to the channel until it becomes idle which marks the maximum $\beta(j,k)$-black-slot burst termination time, and belongs to the node with the highest priority. Then, each node loads its CC with $\max_j \beta(j,k) - \beta(j,k)$. The other counter, SC, is loaded with $n - 1$, in case $\max_j \beta(j,k) - \beta(j,k) = 0$, or an integer random-uniformly selected from $[0, n - 1]$, where $\max \beta(j,k) - \beta(j,k) > 0$. All nodes start down-counting their SCs on subsequent idle channel slots, which signifies the beginning of a transmission phase (TX phase). The scheduling and transmission phases together constitute a PGDMA cycle. When the SC reaches zero, the corresponding CC is decremented by one (if not already zero) and the SC is reinitialized to $n - 1$, in case CC=0, or to a random number in the interval $[0, n - 1]$ otherwise. A packet transmission attempt occurs on SC=0 and CC=0 and according to the IEEE 802.11’s DCF (of course without random back-off). The down-counting stops on a busy channel detection and is resumed on an idle channel detection. Finally, in order for PGDMA to properly sit on top of the IEEE 802.11, there are timing considerations to be addressed. Inequality $T_{PIFS} < T_{NIFS} < T_{DIFS}$ assures backward support for IEEE 802.11’s DCF and PCF, and fulfills the priority requirements of the new class of traffic introduced.

### III. The PGDMA Protocol Analysis

#### A. Dynamic Model of PGDMA Protocol

Since scheduling, which serves as the core to the PGDMA protocol, is based on the accrued cost, we will study how the accrued cost at each node evolves with time. In fact the HoQ-cost vector at the beginning of a specific PGDMA cycle has all the needed information for predicting the future behavior of the system. Referring to the protocol description in Sec. II, it is easily observable that at the end of any PGDMA cycle, a node’s head-of-queue (HoQ) packet will either:

- leave the system upon successful delivery,
- or accumulate cost due to collision and so competing in a higher-priority class during the next PGDMA cycle.

To give a better sense of accumulated costs, from this point on, cost and delay will be used interchangeably without loss of generality, that is $W(\cdot:j,k) = d(j,k)$ where $d(j,k)$ denotes the node $j$’s accumulated delay up to the beginning of the $k$th PGDMA cycle. Assuming a non-empty queue, the experienced delay of the node $j$’s HoQ at the beginning of the $(k+1)$th PGDMA cycle, $d(j,k+1)$, is equal to:

1) the delay up to the beginning of the $k$th PGDMA cycle, $d(j,k)$, plus the $k$th PGDMA cycle period, $T_P(k)$, should this very HoQ has failed in getting through during the $k$th cycle (same HoQ at the beginning of the $k$th and $(k+1)$th cycles) or,

2) the delay up to the beginning of the $k$th PGDMA cycle plus the $(k+1)$th PGDMA cycle interval minus the inter-arrival time between the two consecutive HoQs at the corresponding PGDMA cycles, $T_a(j,k)$, should the previous HoQ has been successfully transmitted during the $k$th cycle (different HoQs at the beginning of the $k$th and $(k+1)$th cycles).

The above two statements can be combined to yield the following expression for the conditional expectation of the delay at the $(k+1)$th cycle given the delay at the $k$th cycle:

$$E[d(j,k+1)|d(j,k)] = [d(j,k) + T_P(k) - T_a(j,k)] + p_s(j,k) [d(j,k) + T_P(k) - (1-p_s(j,k))]$$

$$= d(j,k) + T_P(k) - T_a(j,k) p_s(j,k)$$

(3)

In the above equation, $p_s(j,k)$ represents the node $j$’s probability of successful transmission during the $k$th PGDMA cycle. By specifying $T_P(k)$, $T_a(j,k)$, and $p_s(j,k)$, the recursion (3) models the system’s expected delay under the PGDMA protocol. The inter-arrival packet time, $T_a(j,k)$, is simply specified through related traffic process statistics. The probability of successful transmission, $p_s(j,k)$, is computed from the Binomial distribution as:

$$p_s(j,k) = \sum_{i=1}^{n} \frac{1}{n} \left(\frac{n-1}{n}\right)^{(j,k)-1} \approx 1 - \frac{u(j,k)}{n} + \frac{1}{n}$$

(4)

In (4), $u(j,k)$ denotes the number of node $j$’s classmates including itself at the $k$th PGDMA cycle. Regarding $T_P(k)$’s calculation, $T_P(k)$ comprises the scheduling phase period, $T_{SCHP}(k)$, and the transmission phase period, $T_{TXP}(k)$. The HoQ packets are placed into different classes, $c(j,k) = \max_j \beta(j,k) - \beta(j,k) + 1$, based on their accrued delays where $c(j,k)$ is confined to:

$$\max c(j,k) = \max_j \beta(j,k) - \min_j \beta(j,k) + 1 \leq c_{\max}(k)$$

$$\min c(j,k) = 1$$

(5)

Assuming that at the $k$th PGDMA cycle, and for the $i$th class with population $r(i,k)$, there are $s(i,k)$ successful transmissions (nodes), and $z(i,k)$ collisions involving $r(i,k) - s(i,k)$ nodes, we can write:

$$T_P(k) = T_{SCHP}(k) + T_{TXP}(k) = [\max_j \beta(j,k)] \Delta + \sum_{i=1}^{c_{\max}(k)} [z(i,k) T_{col} + s(i,k) T_s + n \delta] + T_{NIFS}$$

(6)

in which $T_s = T_{RTS} + T_{CTS} + T_{DATA} + T_{ACK} + 3T_{SIFS}$ and $T_{col} = T_{RTS} + T_{CTS} + T_{SIFS}$ are collision and successful transmission time costs, respectively. The
number of successful transmissions and collisions in any class with population \( r \) and size \( n \) (slots) is determined through their joint probability distribution function, \( P(s, z) \), as below:

\[
P(s, z) = \binom{r}{s} \binom{n}{s} \frac{1}{n}^s (1 - \frac{1}{n})^{n-s} \sum_{h_1} \cdots \sum_{h_z} \prod_{w=1}^{z} \left( \frac{r-s - \sum_{m=1}^{w} h_{m-1}}{h_w} \right)
\]

in which \( h_w \in \{2, 3, \ldots, r - s - 2(z - w) - h_{w-1}\} \), \( h_0 = 0 \), and \( w \in \{1, 2, \ldots, z\} \). In (7), the first three multiplicands denote the number of ways \( s \) nodes can be placed in \( n \) possible slots, the fourth multiplicand represents the number of ways \( z \) collisions can be spread over the remaining \( n - s \) slots, and finally the multi-summation quantifies the number of ways \( r - s \) nodes can constitute \( z \) collided groups, counting their order as well.

### B. PGDMA Parameter Optimization

The four parameters, \( n \), \( q \), \( T_{NIFS} \), and \( \Delta \) introduced in (4), (1), (6), and (2), configure the PGDMA protocol. Judicious selection of these parameters is crucial for satisfactory system performance. The lowest possible values for \( \Delta \) and \( T_{NIFS} \) are obviously the best choices since as shown in (6), they linearly affect a PGDMA cycle’s time length without any other secondary effects. As such, \( \Delta = 2\delta \) would be adequate in view of differentiation from \( \delta \) (also cf. Sec. III-D), and \( T_{NIFS} = 2(n + 1)\delta \) guarantees sufficient contention time space for each class to complete all its scheduled transmissions before initiating a new scheduling phase. To obtain optimum values for other parameters we investigate the system behavior under equilibrium condition (steady state) where incoming and outgoing traffic cancel out. We begin with the following assumptions regarding the steady-state (\( k \to \infty \)):

1) the accrued delay at the beginning of a PGDMA cycle, in the steady state, is a time- and node-stationary process i.e. \( d(j, k \to \infty) = d \), where \( d \) is a random variable;

2) the HoQ packets are equally distributed among classes.

The first assumption implies that all delay-related processes, in the steady state, are also node- and time-stationary. In other words, we can write:

\[
\max/\min \beta(j, k) = \beta_{\max/\min}, \quad c_{\max}(k) = c_{\max},
\]

\[
\max/\min d(j, k) = d_{\max/\min}, \quad p_s(j, k) = p_s, \quad u(j, k) = u
\]

Moreover, the second assumption allows us to approximate the average population of each class by \( E[u] = N/M \) where \( E[c_{\max}] = M \).

From the bandwidth efficiency point of view, our goal is to increase the number of successful transmissions while minimizing the scheduling and idle periods (PGDMA protocol overheads), at any PGDMA cycle. This will be done through optimal selection of the class window size, \( n \), and the delay quantization-step, \( q \). The formulation and solution of the underlying optimization problem is outlined as follows.

- Using the intermediate parameter \( M \) for \( q \), the scheduling and idle periods equal \( Mn\delta + 2(M + n)\delta \). So, we define the objective function to be maximized as \( f(M, n) = -Mn - 2(M + n) \).
- Applying expectation to (3), and using the above assumptions, yields the equilibrium equation \( E[T_P] = \frac{1}{\lambda}E[p_s] \). The latter denotes the equality of the average HoQ-packet service time on the LHS and the average HoQ-packet inter-arrival time on the RHS, in the steady state. By enforcing \( \max T_P \leq \frac{1}{\lambda}E[p_s] \), we ensure that the nodes’ queues do not grow indefinitely. Thus, the following serves as the inequality constraint of the optimization problem:

\[
\max T_P - \frac{1}{\lambda}E[p_s] \geq g(M, n) \leq 0 \quad . (8)
\]

- By plugging in \( E[\beta_{\max}] \approx M - 1 \) and \( \max T_P = (M - 1)\Delta + NT_s + Mn\delta + T_{NIFS} \) in (8), the intended optimization problem is then obtained as:

\[
\begin{align*}
\max f(M, n) \text{ subject to } g(M, n) & \leq 0 \quad , \\
f(M, n) = -Mn - 2(M + n) \quad , \\
g(M, n) = M^2n(n + 2)\delta - M[nA + \frac{1}{\lambda} - 2n^2\delta] + \frac{N}{\lambda^2} \quad ; \quad A = \frac{1}{\lambda} - NT_s \quad .
\end{align*}
\]

Finally, \( q^* \) is related to the solution of (9) for \( M^* \) through (5) which yields:

\[
q^* = \frac{E[d_{\max}] - E[d_{\min}]}{M^* - 1} \quad . (10)
\]

Assuming that all packets experience the same average queuing delay, it is straightforward to prove that \( E[d_{\max}] = \frac{N}{(N + 1)\lambda} \) and \( E[d_{\min}] = \frac{N}{(N + 1)\lambda} \).

The optimization problem of (9) is solved using the Lagrange multiplier method and the corresponding results are expressed by the following theorem.

**Theorem III.1** Let \( N \) denote the number of channel-demanding nodes at the beginning of a PGDMA cycle, \( \lambda \) the average packet arrival rate of each node, and \( T_s \) the successful transmission’s time-cost. Then, under the above two assumptions, the optimal values for \( n \) and \( q \) which minimize the PGDMA-cycle intervalare:

\[
\begin{align*}
n^* &= \frac{\sqrt{1 + 4N(1 - NT_s)} - 1}{2(1 + N\delta)} \quad , \\
q^* &= \frac{2(1 - N\delta)}{(N + 1)(M^* - 1)\lambda} \quad ; \quad M^* = n^* \quad . (11)
\end{align*}
\]

### C. Average Total Packet Delay Under PGDMA

Based on the optimal choice of \( n^* \) and \( M^* \) in Sec. III-B, the average total delay of the PGDMA protocol is computed and is later compared against its simulation counterpart.
to investigate the accuracy of the presented mathematical model. Viewing the entire network as a single queueing system with average arrival rate of $N\lambda$ and service rate of $\mu$, the average total packet delay, $E[d] \triangleq D_T$, can be computed using the Little’s formula [4]:

$$D_T = \frac{1}{\mu - N\lambda}. \quad (12)$$

During any PGDMA cycle of length $T_P$, there are $s$ successful packet departures with probability $P(s, z)$ in each $M^*$ priority classes. So, the average packet service rate is computed as follows:

$$\mu = \sum_{s,z} \frac{M^*s}{T_P} P(s, z) \quad (13)$$

in which $T_P$ and $P(s, z)$ are substituted for from (6) and (7), respectively.

D. PGDMA Stability Consideration

Now we verify the stability of the proposed PGDMA protocol, or in other words, the possibility of a delay blow-out. Specifically, we will show that, with node populations below the protocol capacity, the average delay of a representative node $j$ as $t \to \infty$, $E[d(j, k \to \infty)]$, is bounded.

**Theorem III.2** Selection of the parameters $n^*$ and $q^*$ according to (11), the black-slot length of:

$$\Delta < \frac{q^*}{1 + \frac{n^*}{N}} \left[ \frac{n^{*2}}{N - n^*} - 1 \right] \quad (14)$$

guarantees a bounded average delay, $E[d(j, k \to \infty)]$.

**Proof:** Due to the equal delay pile-ups, unsuccessful packets belonging to the same class continue to do so during subsequent cycles. A delay blow-out occurs when packets experience an infinite number of collisions. Such packets, following a transition period, will occupy the highest-priority delay class (the lowest numbered). The population of this class and consequently the probability of a collision occurrence in it decreases with every successful transmission. We tag one of these nodes (node $j$) and denote the time interval from its arrival at the queue up to the beginning of the PGDMA cycle, within which it is placed in the highest-priority delay class for the first time (aforementioned transition period), by $d(j, 0)$. We define the following event:

- $H_{0(j, i)}$: node $j$ has experienced $i$ consecutive collisions following and accrued a delay of $d(j, 0)$ up to the transition period.

Using the above mentioned event, we can write:

$$d(j, k)|_{H_{0(j,k)}} = d(j, k-1)|_{H_{0(j,k-1)}} + T_P(k)|_{H_{0(j,k)}} \quad (15)$$

and it is straightforward to show that:

$$d(j, k)|_{H_{0(j,k)}} \leq (1 + \alpha)^k [d(j, 0) + \frac{B}{\alpha}] - \frac{B}{\alpha} \quad (16)$$

where $B \triangleq \frac{\Delta}{\alpha} + N T_s + T_{NIFS}$, $\alpha \triangleq (1 + \frac{\beta}{\alpha}) \frac{\Delta}{\alpha}$, and $k \in \{1, 2, \ldots\}$. As was stated before, the population of node $j$’s class does not increase. This in turn means that the probability of node $j$ fails its transmission cannot increase by time. Denoting the probability of node $j$ fails in its transmission at the $i$th cycle following the transition period by $p_f(j, i)$, and using (16) we can write:

$$E[d(j, k)|_{H_{0(j,k)}}] = \sum_{i=1}^{k} \prod_{l=1}^{i} p_f(j, i) \left[ 1 - p_f(j, i + 1) \right].$$

$$d(j, i)|_{H_{0(j,i)}} \leq \sum_{i=1}^{k} p_f(j, 1) \left[ 1 - p_f(j, i + 1) \right] d(j, i)|_{H_{0(j,i)}}$$

where in the final step we have used the fact that $p_f(j, i) \geq p_f(j, i) ; \forall i \leq i$. By substituting $d(j, 0)|_{H_{0(j,i)}}$ from (16), and as $k \to \infty$, the RHS of (17) is bounded if and only if:

$$(1 + \alpha) p_f(j, 1) < 1. \quad (18)$$

According to (4) and assuming equal distribution of nodes among classes during this cycle, we obtain:

$$p_f(j, 1) = 1 - p_s(j, 1) = \frac{N - M}{Mn}. \quad (19)$$

Using (19) and (18), it is easily observable that as long as:

$$\Delta < \frac{q^*}{1 + \frac{n^*}{N}} \left[ \frac{n^{*2}}{N - n^*} - 1 \right] \quad (20)$$

where $n^*$ and $q^*$ are adopted according to (11), the stability requirement of (18) is fulfilled.

The initial assignment of $\Delta = 2 \delta$ in Sec. III-B adequately satisfies (20).

IV. SIMULATION RESULTS

The objective in this section is to investigate, through computer simulation, first how accurately the model presented in Sec. III-A captures the dynamics of the system under the PGDMA protocol; and second how the PGDMA protocol performs compared to the conventional IEEE 802.11’s DCF in terms of MoPs of interest such as delay, packet failure rate (PFR), and fairness index (the Jain fairness index [5], $0 \leq F \leq 1$).

A. Simulation Testbed

The PGDMA’s and IEEE 802.11’s MAC layers have been simulated on a sophisticated testbed in the MATLAB environment. The simulation parameters used are shown in Table I. The other PGDMA parameters are selected according to (11). The simulation time is 20 seconds while the results were recorded starting at second 5, letting the transient period elapses. Each point of the graphs has been averaged over 25 repetitions of the simulation. To give a better sense of results’ confidence, the maximum normalized
The IEEE 802.11 standard parameters for DSSS WLANs

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>DATATime/ACKTime</td>
<td>450/20/14/14 octets</td>
</tr>
<tr>
<td>OHMAC/PHY</td>
<td>34/24 octets</td>
</tr>
<tr>
<td>DIFS/SIFS/DTIFS/S</td>
<td>50/10/20 μs</td>
</tr>
</tbody>
</table>

Channel rate - 1 Mbps

**TABLE I**

MAC PARAMETERS USED IN THE SIMULATION.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>DIFS</td>
<td>20 μs ± 12 μs</td>
</tr>
<tr>
<td>DIFS</td>
<td>50 μs ± 4 μs</td>
</tr>
<tr>
<td>Δ</td>
<td>28 μs</td>
</tr>
</tbody>
</table>

**PGDMA parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>NIFS</td>
<td>2(n + 1)</td>
</tr>
<tr>
<td>DIFS</td>
<td>NIFS + 4</td>
</tr>
</tbody>
</table>

**Miscellaneous parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Queue length</td>
<td>30</td>
</tr>
<tr>
<td>TTL</td>
<td>250 ms</td>
</tr>
<tr>
<td>ReTX</td>
<td>10</td>
</tr>
<tr>
<td>X</td>
<td>4.64 packet/s (16 Kbps)</td>
</tr>
<tr>
<td>Simulation time</td>
<td>20 (5+) s</td>
</tr>
</tbody>
</table>

standard deviation of all results are found to be less than 10%. To have a fair basis for comparison, prioritized and non-prioritized source nodes are alike 16-Kbps constant-bit-rate sources.

![Fig. 2. Comparison of analytical and simulation delay results, and system’s MoPs in two different traffic scenarios under the PGDMA scheme compared against the conventional IEEE 802.11.](image)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Datars/Tdats</td>
<td>30</td>
</tr>
<tr>
<td>Dfr</td>
<td>15</td>
</tr>
<tr>
<td>Dpt</td>
<td>20</td>
</tr>
<tr>
<td>Pfrr</td>
<td>0.15</td>
</tr>
<tr>
<td>F</td>
<td>0.9</td>
</tr>
</tbody>
</table>

**B. Results and Discussion**

The upper left plot in Fig. 2 illustrates the normalized average delay time $D_T$ corresponding to (12) and those obtained from simulation in an all-PT scenario. The upper right plot illustrates both theoretical and simulated $D_T$ for the same scenario. The lower left plot illustrates the packet failure rate $P_{fr}$ for various node populations. The lower right plot illustrates the fairness index $F$ for various node populations. All plots illustrate the MoPs of interest in equally-combined NPT/PT and all-PT scenarios. By comparing the two dashed curves in Fig. 2, it can be seen that the PGDMA protocol successfully differentiates between the two types of traffic in the combined traffic case. In fact, the bandwidth is taken away from the NPT to improve delay, packet failure rate, and fairness index among PT carrying nodes. Despite degraded performance of NPT, its results are still acceptable up to PGDMA capacity. Comparing the all-PT (solid line with circular marks) as the worst case under the PGDMA against the IEEE 802.11, it is apparent that: PGDMA outperforms in terms of fairness; equally performs in terms of packet failure rate; and equally performs in terms of delay except for very close-to-capacity node populations (though still below the allowable limit, $TTL$).

**V. CONCLUSION**

To overcome the inherent deficiencies of the conventional IEEE 802.11’s DCF regarding QoS accommodation, a new access technique called Priority-Grouped Distributed Medium Access (PGDMA) is proposed. The protocol distributedly prioritizes packets based on their incurred costs. Packets with equal priorities randomly schedule their transmissions along a contention window. Grouping of the packets is achieved through transmission of a burst of black slots and a mathematical manipulation afterwards, rendering any other information exchange between nodes dispensable. The results show that despite its extra bandwidth consumption for protocol implementation, the new scheme, whose parameters are optimally selected, not only successfully differentiates between PT and NPT, but also outperforms the IEEE 802.11 in an all-PT scenario in terms of service fairness without sacrificing delay and packet failure rate.

**REFERENCES**


