Optimal CWmin Selection for Achieving Proportional Fairness in Multi-Rate 802.11e WLANs: Test-bed Implementation and Evaluation*

Vasilios A. Siris† and George Stamatakis
Institute of Computer Science, FORTH
P. O. Box 1385, GR 711 10 Heraklion, Crete, Greece
vsiris@ics.forth.gr, gstam@ics.forth.gr

ABSTRACT

We investigate the optimal selection of minimum contention window values to achieve proportional fairness in a multi-rate IEEE 802.11e test-bed. Unlike other approaches, the proposed model accounts for the contention-based nature of 802.11's MAC layer operation and considers the case where stations can have different weights corresponding to different throughput classes. Our test-bed evaluation considers both the long-term throughput achieved by wireless stations and the short-term fairness. When all stations have the same transmission rate, optimality is achieved when a station's throughput is proportional to its weight factor, and the optimal minimum contention windows also maximize the aggregate throughput. When stations have different transmission rates, the optimal minimum contention window for high rate stations is smaller than for low rate stations. Furthermore, we compare proportional fairness with time-based fairness, which can be achieved by adjusting packet sizes so that low and high rate stations have equal successful transmission times, or by adjusting the transmission opportunity (TXOP) limit so that high rate stations transmit multiple back-to-back packets and thus occupy the channel for the same time as low rate stations that transmit a single packet. The test-bed experiments show that when stations have different transmission rates and the same weight, proportional fairness achieves higher performance than the time-based fairness approaches, in terms of both aggregate utility and throughput.

*This work has been supported by British Telecom, UK and the General Secretariat for Research and Technology, Greece.

†The first author is also with the Department of Computer Science, University of Crete, Heraklion, Greece.

WiNTECH'06, September 29, 2006, Los Angeles, California, USA.

Categories and Subject Descriptors

C.2.1 [**Computer-Communication Networks**]: Network Architecture and Design—*wireless communication, network communications*

General Terms

Experimentation, Performance

Keywords

Fairness definition, short-term fairness, throughput differentiation

1. INTRODUCTION

As IEEE 802.11 wireless networks become more ubiquitous, they will be the primary access technology for connecting to the Internet and enterprise networks. The 802.11b standard can support transmission rates up to 11 Mbps, whereas the newer standards 802.11a/g support transmission rates up to 54 Mbps. Hence, the available bandwidth in wireless LANs is at least one order of magnitude smaller than the capacity typically available in wired networks. Moreover, emerging multimedia services over wireless networks will have different bandwidth and delay requirements. For all the above reasons, resource control and service differentiation in 802.11 wireless LANs is becoming increasingly important.

The recent IEEE 802.11e standard supplement introduces MAC layer mechanisms for QoS support. There are only a few works that have investigated 802.11e mechanisms in an actual test-bed [13, 1, 7, 6]. The work in [13] investigates fairness for uplink TCP flows, showing that fairness can be significantly improved if TCP acknowledgements flowing from the access point to the wireless stations are given priority over data packets. An investigation of 802.11e mechanisms for giving priority to voice traffic is contained in [6]. The work in [7] investigates long-term unfairness in 802.11 networks, and proposes various methods for restoring fairness. All the above works define fairness as the achievement of equal throughput by all stations. Finally, the work in [1] investigates bandwidth sharing using the various mechanisms provided by 802.11e. Our work differs from the above in that we consider multi-class and multi-rate 802.11 networks, we consider proportional fairness which differentiates stations with different transmission rates, and we investigate short-term fairness in addition to the long-term throughput achieved by different wireless stations.

Representative work dealing with 802.11 fairness in various contexts, but without involving results from actual test-bed experimentation, is contained in [14, 16, 8, 19, 15, 9, 20]. In particular, the work in [14] considers weighted fairness, where bandwidth is shared in proportion to weights. The works of [16, 9, 19, 20] discuss the notion of time-based (or temporal) fairness, which tries to equalize the time the wireless channel is occupied by stations transmitting at different rates. On the other hand, we consider proportional fairness, which tries to maximize the aggregate utility of all flows in the network. The work of [15] also advocates the use of proportional fairness in multi-hop wireless networks. In this paper, we compare in an actual test-bed environment the proportional fairness scheme implemented by controlling the minimum contention window CW_{min} with time-based fairness implemented by adjusting the packet size or the transmission opportunity TXOP limit parameter so that all stations acquire the wireless channel for an equal duration.

The rest of the paper is organized as follows. In Section 2 we present a brief overview of the DCF and EDCA mechanisms in IEEE 802.11e. In Section 3 we first discuss an analytical throughput expression for multi-rate 802.11e networks, and then present the proposed proportional fairness model. In Section 5 we present test-bed experiments that evaluate and compare the proportional fairness model with the time-based fairness model. Finally, in Section 6 we conclude the paper identifying future research directions.

2. IEEE 802.11E AND EDCA

IEEE 802.11's DCF (Distributed Coordination Function) is based on CSMA/CA (Carrier Sense Multiple Access with Collision Avoidance). According to the collision avoidance mechanism of CSMA/CA, a station performs a backoff procedure before initiating the transmission of a frame. After detecting that the medium is idle for a DIFS (DCF inter-frame spacing) interval, the station selects a random backoff period from $[0, CW-1]$, where CW is referred to as contention window. The station waits for the channel to be idle for a total time equal to this backoff period, after which it can transmit a data frame with the basic CSMA/CA procedure, or an RTS frame with the RTS/CTS procedure. The contention window CW has an initial value CW_{min}, and is doubled when a collision occurs, up to the maximum value CW_{max}. When a frame is successfully transmitted, the contention window is set to its initial value CW_{min}.

The IEEE 802.11e standard supplement addresses the issue of QoS support in wireless LANs. The MAC protocol of 802.11e is the Hybrid Coordination Function (HCF), which supports both contention-based and controlled channel access. The contention-based access of HCF is supported by the Enhanced Distributed Channel Access (EDCA) mechanism, which is an extension of the DCF mechanism that enables distributed differentiated access to the wireless channel with the support of multiple access categories (ACs). A higher priority access category has a smaller minimum contention window CW_{min}, thus has a higher probability to access the channel. Additionally, different access categories can have a different maximum contention window CW_{max} and a different interframe spacing interval (IFS), which is now called Arbitration IFS (AIFS). Although the IEEE 802.11e standard defines a number of parameters that can be used to achieve service differentiation, it does not define how these parameters should depend on the network load and traffic characteristics in order to efficiently utilize the shared wireless channel.

3. OPTIMAL $CW_{\min}$ FOR ACHIEVING PROPORTIONAL FAIRNESS IN EDCA

In this section we first present a simple throughput expression for multi-rate IEEE 802.11e networks using the EDCA mechanism. Then, based on this throughput expression we present a model for achieving proportional sharing of the wireless channel that takes into account the contention-based nature of the EDCA mechanism.

3.1 Throughput model for EDCA

Several analytical studies have approximated IEEE 802.11's congestion avoidance procedure with a p-persistent model [5, 14]. In a p-persistent model, the probability p that a station tries to transmit in a time slot is independent of the success or failure of previous transmission attempts. The p-persistent model closely approximates the throughput of the actual congestion avoidance procedure when the average backoff is the same [5]; moreover, the saturation throughput has a small dependence on the exact backoff distribution [11].

If $E[CW]$ is the average contention window, then the approximate p-persistent model has transmission probability $p = \frac{2}{E[CW]+1}$ [5]. If the probability of a frame being involved in more than one collision is very small, then $E[CW] \approx CW_{min}$ [14]. In IEEE 802.11e, different wireless stations can have a different minimum contention window, hence using the same arguments as above [14], the transmission probability of station i in the p-persistent model is related to its minimum contention window through

$$p_i = \frac{2}{CW_{min,i}+1}\,. \tag{1}$$

The MAC operation of IEEE 802.11 can be viewed in time as involving three different types of time intervals: a successful transmission interval, a collision interval, and an idle time interval. We denote the length of the successful and collision interval T^{suc}, T^{col}, respectively. The length of the idle interval is equal to one time slot. The duration of each time interval depends on the physical layer encoding and the MAC layer operations. For basic CSMA/CA in 802.11b, T^{suc} is given by[1]:

$$T^{suc} = 2T_{PHY} + T_{SIFS} + \frac{8(O+L)}{R} + T_{ACK} + T_{DIFS}\,, \tag{2}$$

where L is the frame length, O is the size of the MAC header and if present the optional LLC/SNAP header, R is the transmission rate, and T_{PHY}, T_{SIFS}, T_{DIFS}, T_{ACK} are the physical layer overhead, SIFS interval, DIFS interval, and ACK transmission time, respectively. The collision interval T^{col} is

$$T^{col} = T_{PHY} + \frac{8(O+L)}{R} + T_{DIFS}\,. \tag{3}$$

For RTS/CTS the successful transmission and collision intervals can be computed in a similar manner, taking into

[1] We assume that the propagation delay is very small, hence do not consider it.

account that in 802.11b the ACK, RTS, and CTS frames are always transmitted at the basic rate (1 or 2 Mbps), hence their transmission times are independent of the rate R.

The above model can also be applied to uplink TCP traffic, if we assign a higher priority to TCP acknowledgments flowing from the access point to the wireless stations and appropriately select the duration of the collision interval [12, 17]. In this case, the probability of TCP acknowledgements colliding can be considered negligible, and the successful transmission interval would include the transmission of a TCP acknowledgement. In this paper we assign higher priority for TCP acknowledgements by assigning them $AIFS = 1$ and $CW_{min} = 2$. Because TCP delayed acknowledgements are set on by default in the Linux implementations used in our test-bed, on the average each successful transmission of a data packet will involve half the time necessary to transmit a TCP acknowledgement. Hence, the duration of the successful transmission interval for TCP, when TCP acknowledgements are sent with $AIFS = 1$ and $CW_{min} = 2$, is approximately

$$\begin{aligned} T^{TCP,suc} \;=\;& 2T_{PHY} + T_{SIFS} + \frac{8(O+L)}{R} + T_{ACK} + T_{DIFS} + \\ & \frac{1}{2}\Big(2T_{PHY} + T_{SIFS} + \frac{8(O+L_{TCPACK})}{R} + T_{ACK} + T_{AIFS=1} \\ & + \frac{T_{slot}}{2}\Big)\,, \end{aligned} \tag{4}$$

where $L_{TCPACK} = 40$ bytes is the length of a TCP acknowledgement, $T_{AIFS=1} = T_{SIFS} + Slot\_Time$ is the time duration for $AIFS = 1$, and $\frac{T_{slot}}{2}$ is the average backoff duration for $CW_{min} = 2$.

The average throughput for station i, considering a renewal assumption, can be expressed as the ratio of the average amount of data transmitted by that station in one time interval over the average time interval $x_i = \frac{E[X_i]}{E[T]}$ [3, 5, 14]. The average data transmitted by station i in one time interval, considering a p-persistent model and assuming that the station always has a frame ready to transmit, is $E[X_i] = p_i \prod_{j\neq i}(1-p_j)L$, where L is the frame size, which for simplicity we assume is the same for all stations. The average time interval is a weighted sum of the three types of intervals. If we assume that the intervals T^{suc} and T^{col} are normalized to the size of the idle slot time, and if all stations have the same transmission rate, then the average time interval is

$$\begin{aligned} E[T] \;=\;& \sum_k p_k \prod_{j\neq k}(1-p_j)T^{suc} + \\ & \left[1 - \prod_j(1-p_j) - \sum_k p_k \prod_{j\neq k}(1-p_j)\right] T^{col} + \\ & \prod_j (1-p_j)\,, \end{aligned} \tag{5}$$

where $j \in I_k$. From the above, the average throughput x_i for station i is approximately

$$x_i = \frac{p_i \prod_{j\neq i}(1-p_j)L}{E[T]}\,, \tag{6}$$

where $E[T]$ is given by (5). Note that the above expression is valid under saturation conditions, when stations always have a packet to transmit, and can be applied to all versions of 802.11 and when TCP is used, provided that acknowledgements flowing from the access point to the wireless stations are given priority. The specific version of 802.11, and whether the CSMA/CA or RTS/CTS procedure is used, will determine the values of T^{suc} and T^{col}, which we have taken to be normalized to the duration of the idle interval.

Next we consider the case where different stations have different transmission rates. In 802.11b with RTS/CTS, the transmission rate does not affect the collision interval, since the latter involves RTS frames which are always transmitted at the basic rate (1 or 2 Mbps). Hence, for 802.11b with RTS/CTS, the average time interval is

$$\begin{aligned} E[T] \;=\;& \sum_k p_k \prod_{j\neq k}(1-p_j)T_k^{suc} + \\ & \left[1 - \prod_j(1-p_j) - \sum_k p_k \prod_{j\neq k}(1-p_j)\right] T^{col} + \\ & \prod_j (1-p_j)\,, \end{aligned} \tag{7}$$

where the duration of the successful transmission interval T_k^{suc} depends the station's transmission rate through (2).

In 802.11 with the basic CSMA/CA procedure, the collision interval also depends on the transmission rate. In this case the second term in (7) needs to be modified appropriately, to account for the fact that packet collisions can involve a low rate station, or be between high rate stations. We discuss this further in Section 3.2.2.

3.2 Optimal $CW_{\min}$ selection for achieving proportional fairness

In this section we discuss the optimal selection of CW_{min} so that the wireless channel is shared in a proportionally fair manner. Weighted proportional fairness can be defined by considering that each station has a logarithmic utility $U(x_i) = w_i \log(x_i)$ [10], where w_i and x_i is the weight and throughput for station i, respectively. If N is the number of stations, then the optimal transmission probabilities, hence the optimal minimum contention windows, are determined by the following problem

$$\begin{aligned} \text{maximize} \quad & \sum_i w_i \log(x_i) \\ \text{over} \quad & \{p_i \geq 0, 1 \leq i \leq N\}\,, \end{aligned} \tag{8}$$

where the throughput x_i for station i is given by (6). From the optimal transmission probabilities, the optimal minimum contention windows can be determined from (1).

3.2.1 *Singe transmission rate*

If all stations have the same physical layer transmission rate, then one can show that to achieve optimality, the average throughput should be proportional to the weight factor of a station's utility [18]. Hence, from (6) it follows that the transmission probability should be proportional to the weight factor, and from (1) it follows that the optimal minimum contention window should be approximately inversely proportional to the weight factor. Additionally, when all stations have the same transmission rate, maximizing the aggregate utility is equivalent to maximizing the aggregate throughput.

If w_i is the weight for station i, then the optimization in (8) can be performed over a single transmission probability. If, without loss of generality, we assume that the optimization is over p_0, then the other transmission probabilities are given by $p_i = w_i p_0 / w_0$.

One can obtain closed form approximations for the optimal transmission probabilities when stations have the same weight [5, 4, 9] or different weights [18]. Because the focus of this paper is on evaluating the optimal selection of CW_{min} values in an actual test-bed, we need to consider that in actual implementations CW_{min} can only obtain values that are powers of 2. Moreover, since the aggregate throughput has a unimodal dependance on the transmission probability, hence the minimum contention window, there is a single value of p_0 that maximizes the sum of utilities, which can be found using a simple search approach. Indeed, when the number of stations is a few 10s, then it is sufficient to search for the optimal minimum contention window in the range 2^5 to 2^{10} (a total of 6 values). Moreover, note that 2^{10} is the maximum value of CW_{min} that is supported by current implementations.

3.2.2 Multiple transmission rates

If different stations have different transmission rates, and the RTS/CTS mechanism is used, then only T^{suc} depends on the transmission rate, whereas T^{col} is independent of transmission rate. In this case, one can show [18] that the optimal values of p_i satisfy the following equation

$$p_i = \frac{w_i}{\sum_j w_j} \frac{(1-P)E[T]}{(1-P)^2 T_i^{suc} + P(2-P)T^{col}}\,, \qquad (9)$$

where $P = \sum p_i$ and $E[T]$ is given by (7). The equation $P = \sum p_i$, with p_i is given by (9), can be solved as a fixed point equation.

Aside using (9) one can also apply a brute force search method similar to the one discussed in the previous subsection. If we have two different transmission rates and n possible values of CW_{min}, then the brute force search would be order $O(n^2)$. As noted above, n is typically 6 (for CW_{min} values ranging from 2^5 to 2^{10}), hence in practical situations the computational cost of such a search is small. Additionally, one can reduce the search space by considering that low rate stations will have a larger CW_{min} than high rate stations.

Next we consider the closed-loop distributed control scheme discussed in [18]; although such a procedure is not considered in our experiments, it is helpful for explaining how stations with different transmission rates should be handled under proportional fairness. The global optimization of the aggregate utility can be achieved in a distributed manner if each station selects its minimum contention window, which determines the throughput it achieves, based on the following optimization

$$\begin{array}{ll} \text{maximize} & w_i \log(x_i) - (\mu_1 T_i^{suc} + \mu_2 T^{col}) x_i \\ \text{over} & p_i \geq 0\,, \end{array}$$

where μ_1, μ_2 are congestion factors, the same for all users, which depend on the level of contention in the wireless channel; the right-hand term in the above objective function depicts the congestion cost. The last equation shows that a low rate station would receive a higher congestion cost, due to the higher value of T_i^{suc}. Moreover, note that there is another term in the congestion cost that is independent of the transmission rate, and corresponds to the congestion cost due to collisions. The relative contribution of the two terms to the total congestion cost is determined by the ratio μ_1/μ_2, which depends on the level of contention in the wireless channel.

If the basic CSMA/CA mechanism is used, then the collision interval T^{col} depends on the transmission rate; this also occurs when the RTS/CTS mechanism is used and there are stations with transmission rate 1 Mbps, in which case control packets are transmitted with basic rate 1 Mbps, and stations with transmission rate equal or higher than 2 Mbps, in which case control packets are transmitted with basic rate 2 Mbps. The extension to the case where the transmission rate also affects T^{col} cannot be simply done by assuming that the feedback related to the cost of collisions depends on its transmission in an identical way as the cost of successful transmissions depends on the transmission rate. The reason is that when two packets from stations with different transmission rates collide, then the channel cannot be used for an interval equal to the time required to transmit a packet from the slowest station. In the test-bed experiments presented in Section 5 we consider an approximation which assumes that collisions involving 3 or more stations are negligible. Based on this assumption, in equations (5), (7), and (9) we replace T^{col} with a weighted average $\overline{T^{col}}$, where weights correspond to the probability that a collision involves at least one low transmission rate station, and the probability that it involves only high transmission rate stations.

4. IEEE 802.11E TEST-BED

The topology for the experiments reported in this paper is shown in Figure 1. It consists of a Linux-based access point and 11 workstations. All systems run Linux kernel version 2.6.16, and are equipped with an Atheros 802.11a/b/g PCMCIA card and the MadWiFi driver (version madwifi-ng-r1527-20060425). We have also conducted experiments with a production (Cisco) access point supporting 802.11e mechanisms and Windows-based stations, equipped with the same Atheros 802.11a/b/g PCMCIA card. However, to avoid potential influences from the different wireless drivers, in the experiments we present in this paper we consider solely the Linux-based stations. Finally, the wireless stations are placed at a random location within approximately 2−5 meters from the base station; the same positioning of the stations is maintained for the scenarios that are compared.

The module for selecting the optimum CW_{min} parameters runs on a workstation that communicates the optimal values to the access point through SNMP, in the case of the production access point. In the case of the Linux access point, the CW_{min} selection module can run on the access point. The module takes as input the number of stations, their weights, and their transmission rates. The weights can correspond to a throughput class that is either pre-configured or selected by stations during their association to the access point. The transmission rates for stations is available at the access point. Finally, the number of stations can be dynamically estimated based on the recent activity of stations. The optimal CW_{min} values are computed once, at the beginning of each experiment, since the traffic remains the same throughout each experiment. Finally, according to the IEEE 802.11e standard, the values of the 802.11e MAC layer parameters are broadcasted to the wireless stations using beacon frames.

We assume all stations and the access point use the 802.11b standard. Finally, in the experiments we consider constant bit rate traffic (with rate 5 Mbps), generated by Iperf and flowing from the wireless stations to the station connected

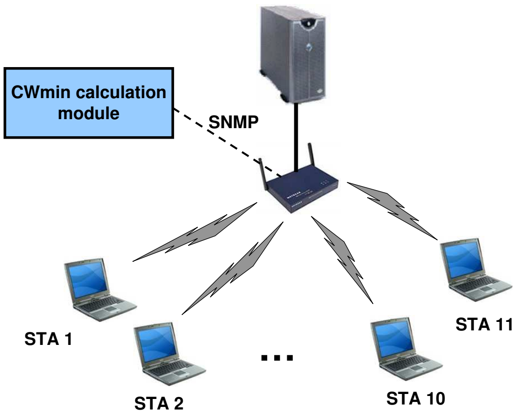

Figure 1: IEEE 802.11e testbed.

to the access point through a wired link, Figure 1. The throughput results presented are averages from 300 seconds.

5. PERFORMANCE EVALUATION

In this section we present and discuss the results from the application of the optimal CW_{min} selection method in the test-bed described above. The evaluation is in terms of fairness and throughput. To measure short-term fairness we consider the sliding window application of Jain's fairness index as defined in [2], adapted to the case where different stations can have different weights. In particular, let $y_i(K) = z_i(K)/w_i$, where $z_i(K)$ is the fraction of transmissions performed by station i in some window K and w_i is the weight for station i. The fairness index for window K is defined as

$$Fairness\_Index(K) = \frac{(\sum_{i=1}^{N} y_i(K))^2}{N\sum_{i=1}^{N} y_i^2}.$$

Absolute fairness is achieved when the fairness index is equal to 1, whereas the value $1/N$ corresponds to the case where only one station transmits. Similar to [2], we consider the normalized window size M, which is related to the window size K and the stations' weights through $K = M \times \sum_{i=1}^{N} w_i$, where N is the number of stations. The results contained in this section show the fairness index as a function of the normalized window size.

The various parameters used by the MadWifi driver are shown in Table 1. In addition to inspecting the driver source code, the values of the parameters were verified using the AirMagnet Laptop Analyzer (version 6.1). Observe that the packet overhead is 34 bytes, which includes the 26 bytes MAC overhead and an 8 bytes LLC/SNAP header. The MAC overhead is smaller than the typical value in the 802.11 standard (34 bytes) because one 6 bytes address and the 4 bytes FCS (Frame Check Sequence) fields are absent, and 802.11e includes a 2 bytes "QoS" field. Additionally, observe that the length of the RTS/CTS and ACK packets is smaller by 4 bytes than the typical value noted in the standard because the FCS (Frame Check Sequence) is absent.

5.1 Same transmission rate / multiple weights

We first consider the case where all stations have the same transmission rate, but different weights. The optimal minimum contention window values are computed as discussed in Section 3.2.1. The experiments involved a total of 11 stations, of which 6 had weight w_{hi} and 5 with weight w_{low}. In particular, Figure 2 is for $w_{hi} = 2, w_{low} = 1$ and Figure 2 is for $w_{hi} = 4, w_{low} = 1$. Both figures contain results with UDP traffic. Tables 2 and 3 show, for the same experiments, the aggregate throughput achieved and the window size for which a fairness index of 0.95 is achieved.

Figures 2 and 3 show that increasing CW_{min} results in improved fairness. However, the fairness improvements when $\log(CW_{min})$ increases from $(5,6)$ to $(6,7)$, which are the optimal values that maximize the aggregate utility, are larger than the improvements when we further increase $\log(CW_{min})$ to $(7,8)$. Additionally, observe from Table 2 that the optimum values $(6,7)$ achieve the maximum aggregate throughput. Similar observations can be made from Figure 3 and Table 3. Moreover, comparison of Figure 2 with Figure 3 and Table 2 with Table 3 show that increasing the variability of the network results in lower short-term fairness.

Figure 4 and Table 4 show the results in the case of TCP traffic, when TCP acknowledgements are given higher pri-

Table 1: Parameters used in the experiments

Parameter	Value
T_{slot}	20 μs
T_{DIFS}, T_{SIFS}	$50, 10$ μs
O (MAC+LLC/SNAP overhead)	34 bytes
T_{PHY}	96 μs (short preamble)
$T_{ACK} = T_{CTS}$, T_{RTS}	$10, 16$ bytes
R_{basic}	1 or 2 Mbps

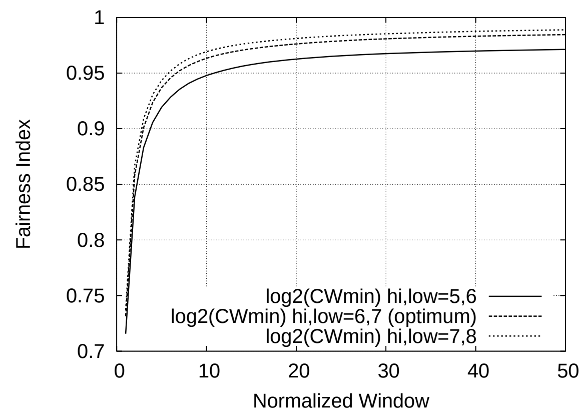

Figure 2: Fairness index. UDP traffic, $N_{hi} = 6, w_{hi} = 2, N_{low} = 5, w_{low} = 1$

Table 2: Throughput and window size to achieve 0.95 fairness index. UDP traffic, $N_{hi} = 6, w_{hi} = 2, N_{low} = 5, w_{low} = 1$**.**

$\log(CW_{min})$ hi,low	Throughput (Mbps)	Window size
5,6	6.64	17
6,7	6.67	11
7,8	6.32	9

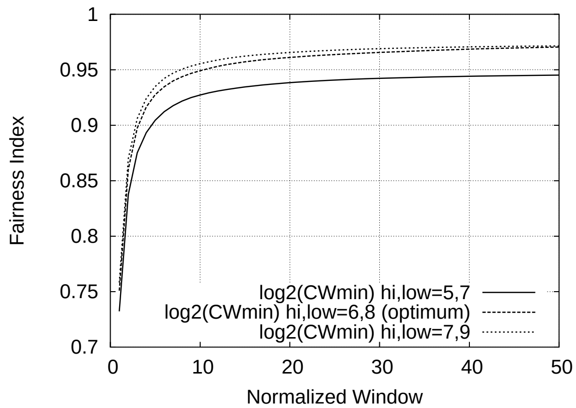

Figure 3: Fairness index. UDP traffic, $N_{hi} = 6, w_{hi} = 4, N_{low} = 5, w_{low} = 1$

Table 3: Throughput and window size to achieve 0.95 fairness index. UDP traffic, $N_{hi} = 6, w_{hi} = 4, N_{low} = 5, w_{low} = 1$**.**

$\log CW_{min}$ hi,low	Throughput (Mbps)	Window size
5,7	6.48	>100
6,8	6.49	28
7,9	6.05	21

ority (Section 3.1). Comparison with Figure 2 and Table 2 shows that the introduction of TCP can result in lower short-term fairness.

5.2 Multiple transmission rates / same weight

Next we consider the case where different stations have different transmission rates, but the same weight. This corresponds to the case where all stations have the same utility for their average throughput. It is well known that in multi-rate situations the aggregate throughput can decrease significantly, and all stations achieve the same average throughput independent of their transmission rate [8]. In our experiments, 6 stations transmit at hi rate (11 Mbps) and 5 stations transmit at low rate (1 Mbps).

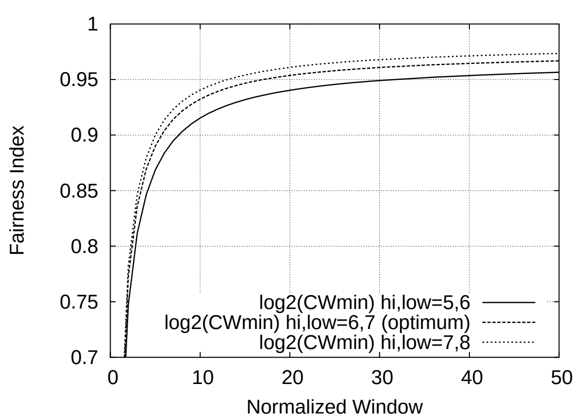

Figure 4: Fairness index. TCP traffic, $N_{hi} = 6, w_{hi} = 2, N_{low} = 5, w_{low} = 1$

Table 4: Throughput and window size to achieve 0.95 fairness index. TCP traffic, $N_{hi} = 6, w_{hi} = 2, N_{low} = 5, w_{low} = 1$**.**

$\log CW_{min}$ hi,low	Throughput (Mbps)	Window size
5,6	5.70	36
6,7	6.13	18
7,8	6.11	14

Figure 5 compares the throughput achieved by the normal 802.11 MAC with RTS/CTS, which achieves equal throughput for all stations, with the throughput achieved by proportional fairness and time-based (or temporal) fairness [16, 19, 20, 9]. To achieve time-based fairness we consider two approaches: The first adjusts the packet size so that the time occupied by the transmission of one packet is the same for hi and low rate stations. The second approach adjusts the transmission opportunity (TXOP) limit so that the time occupied by both low and hi and low rate stations, once they acquire the channel, is the same. Observe that when the packet size is used to achieve time-based fairness the low rate stations are significantly penalized, achieving an average throughput approximately 27 Kbps, while high rate stations achieve an average throughput of 467 Kbps, i.e. more than 17-fold difference. This is because the packet size for low rate stations is reduced to 78 bytes so that its transmission has the same duration as the transmission of one packet (1472 bytes) by the high rate stations. The packet size for high rate stations was set to 1472 bytes so that it is less than the maximum transmission unit (MTU) in Ethernet networks. The very small packet size for low rate stations results in the header overhead being a significant proportion of the whole packet, compared to the case of high rate flows.

When the transmission opportunity (TXOP) parameter is used to achieve time-based fairness, Figure 5, low rate stations are penalized less compared to the packet size adjustment approach. This is because now the overhead associated with low rate stations is lower than the overhead with the packet size method, where the packet size was 78 bytes. With the TXOP approach, the packet size is set to 720 bytes and the TXOP limit is set to 6864 μs; the maximum value for the TXOP limit supported by the MadWifi driver is 8000 μs. With proportional fairness the optimal values of the minimum contention window is 2^5 and 2^8 for the high and low rate stations respectively, and compared to the packet size adjustment approach the low rate stations are not penalized as much, achieving an average throughput of approximately 69 Kbps, while high rate stations achieve an average throughput of approximately 594 Kbps, i.e. less than 9-fold difference. Figure 5 also shows that low rate stations achieve approximately the same average throughput with the time-based fairness approach using the TXOP parameter and the proportional fairness approach using the CW_{min} parameter. On the other hand, high rate stations achieve a higher throughput with the proportional fairness approach compared to the time-based fairness approach using the TXOP parameter.

Figure 6 shows the aggregate throughput achieved by the different approaches. Observe that all fairness schemes achieve a higher aggregate throughput compared to the normal 802.11 operation where stations achieve equal throughput, indepen-

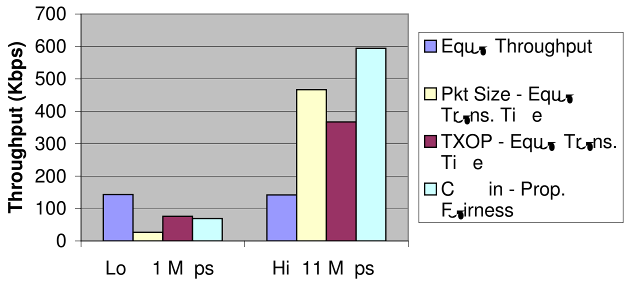

Figure 5: Throughput of hi and low rate stations with different fairness approaches. RTS/CTS

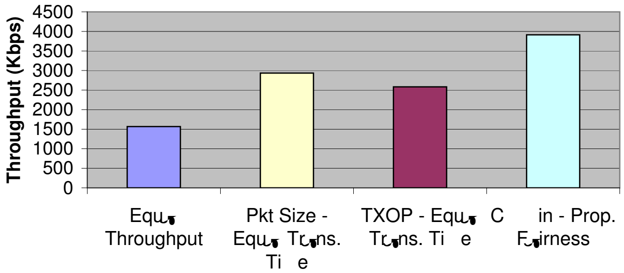

Figure 6: Aggregate throughput achieved by different fairness approaches. RTS/CTS

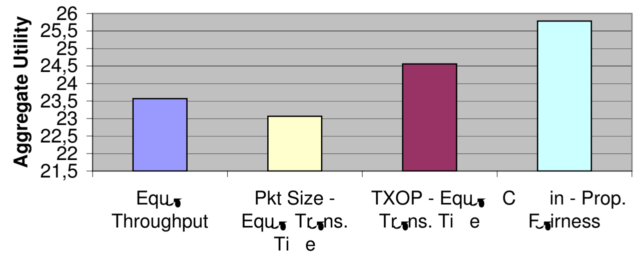

Figure 7: Aggregate utility achieved by different fairness approaches. RTS/CTS

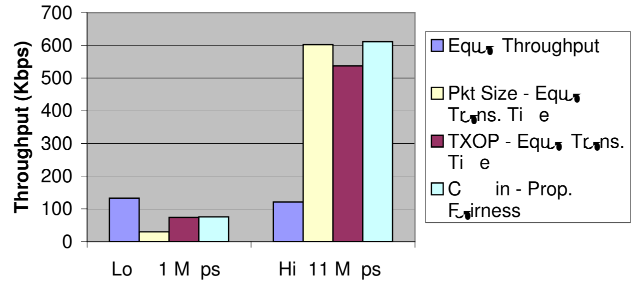

Figure 8: Throughput of hi and low rate stations with different fairness approaches. Basic CSMA/CA.

dent of their transmission rate. Moreover, the packet size adjustment method achieves higher throughput compared to the TXOP approach, because it penalizes low rate flows more. On the other hand, the proportional fairness approach with adjustment of the CW_{min} values achieves a higher throughput primarily by increasing the average throughput of high rate stations (594 Kbps compared to 376 Kbps achieved by the TXOP approach), with a small decrease of the average rate achieved by low rate stations (69 Kbps compared to 76 Kbps achieved by the TXOP approach). The aggregate utility achieved by all approaches is shown in Figure 7; as expected, the aggregate utility achieved by the proportional fairness approach is highest, whereas the lowest aggregate utility is achieved by the packet size adjustment approach. Finally, Figure 8 shows the throughput achieved by high and low rate stations for the different fairness approaches, when the basic CSMA/CA procedure is used. Observe that with the basic CSMA/CA procedure, the throughput achieved by the high rate stations under the two equal transmission time schemes is closer to the throughput achieved under proportional fairness.

6. CONCLUSIONS

We have presented and discussed test-bed results from the optimal selection of minimum contention window values to achieve proportional fairness. In the case of stations with the same transmission rate but different weights, we presented experimental results showing the short-term fairness, and how it is affected by the weights and the use of UDP or TCP. Additionally, the comparison of the proposed proportional fairness approach when stations have the same weight, with the time-based fairness approach achieved by adjusting the packet size or the transmission opportunity limit shows that the former achieves higher performance in multi-rate scenarios, in terms of both aggregate utility and throughput.

Another approach for approximating time-based fairness is to adjust the ratio of the minimum contention windows for different rate stations [9], so that the *average* time occupied for the successful transmission of data is the same for stations with different rates. Experimental results show that this approach can accurately determine the optimal ratio of the minimum contention window values, but alone cannot be used to determine the absolute values of CW_{min}, as the proportional fairness approach described in Section 3.2.2. One issue with differentiation using the CW_{min} parameter is that because its values are limited to powers of 2, the differentiation granularity is crude. Hence, investigating the combined use of the CW_{min} and the TXOP parameters for achieving service differentiation and fairness is interesting.

Our focus in this paper was on the uplink direction. In the downlink direction, proportional fairness is achieved if the average throughput is inversely proportional to duration of successful transmission. In addition to experiments involving traffic in the downlink direction, we are investigating the optimal selection of parameters when best-effort traffic co-exists with real-time traffic.

7. REFERENCES

[1] A. Banchs, A. Azcorra, C. Garcia, and R. Cuevas. Applications and Challenges of the 802.11e EDCA Mechanism: An Experimental Study. *IEEE Network*, pages 52–58, July/August 2005.

[2] G. Berger-Sabbatel, A. Duda, O. Gaudoin, M. Heusse, and F. Rousseau. Fairness and its Impact on Delay in 802.11 Networks. In *Proc. of IEEE Globecom*, 2004.

[3] G. Bianchi. Performance analysis of the IEEE 802.11 distributed coordination function. *IEEE J. Select. Areas Commun.*, 18(3):535–547, March 2000.

[4] L. Bononi, M. Conti, and E. Gregori. Runtime Optimization of IEEE 802.11 Wireless LANs Performance. *IEEE Trans. on Parallel and Distributed Systems*, 15(1):66–80, 2004.

[5] F. Cali, M. Conti, and E. Gregori. Dynamic tuning of the IEEE 802.11 protocol to achieve a theoretical throughput limit. *IEEE/ACM Trans. on Networking*, 8(6):785–799, 2000.

[6] I. Dangerfield, D. Malone, and D. J. Leith. Experimental Evaluation of 802.11e EDCA for Enhanced Voice over WLAN Performance. In *Proc. of 2nd Int'l Workshop on Wireless Network Measurement (WiNMee)*, 2006.

[7] S. Ganu, K. Ramachandran, M. Gruteser, I. Seskar, and J. Deng. Methods for Restoring MAC Layer Fairness in IEEE 802.11 Networks with Physical Layer Capture. In *Proc. of 2nd ACM Int'l Workshop on Multi-hop Ad Hoc Networks: from Theory to Reality (REALMAN)*, 2006.

[8] M. Heusse, F. Rousseau, G. Berger-Sabbatel, and A. Duda. A performance anomaly of IEEE 802.11. In *Proc. of IEEE INFOCOM*, 2003.

[9] M. Heusse, F. Rousseau, R. Guillier, and A. Duda. Idle Sense: An Optimal Access Method for High Throughput and Fairness in Rate Diverse Wireless LANs. In *Proc. of ACM SIGCOMM*, 2005.

[10] F. P. Kelly. Charging and rate control for elastic traffic. *European Transactions on Telecommunications*, 8:33–37, January 1997.

[11] A. Kumar, E. Altman, D. Miorandi, and M. Goyal. New Insights from a Fixed Point Analysis of Single Cell IEEE 802.11 WLANs. In *Proc. of IEEE INFOCOM*, 2005.

[12] D. J. Leith and P. Clifford. Using the 802.11e EDCF to Achieve TCP Upload Fairness over WLAN Links. In *Proc. of 3rd Int'l Symposium on Modeling and Optimization in Mobile, Ad Hoc, and Wireless Networks (WiOpt)*, 2005.

[13] A. Ng, D. J. Leith, and D. W. Malone. Experimental Evaluation of TCP Performance and Fairness in an 802.11e Test-bed. In *Proc. of ACM SIGCOMM Workshop on Experimental Approaches to Wireless Network Design and Analysis*, 2005.

[14] D. Qiao and K. G. Shin. Achieving efficient channel utilization and weighted fairness for data communications in IEEE 802.11 WLAN under DCF. In *Proc. of IEEE/IFIP International Conference of Quality of Service (IWQoS'02)*, 2002.

[15] B. Radunovic and J.-Y. L. Boudec. Rate Performance Objectives in Multi-hop Wireless Networks. In *Proc. of IEEE INFOCOM*, 2004.

[16] B. Sadeghi, V. Kanodia, A. Sabharwal, and E. Knightly. Opportunistic Media Access for Multirate Ad Hoc Networks. In *Proc. of ACM MOBICOM*, 2002.

[17] V. A. Siris and P. Alafouzos. Throughput Differentiation for TCP Uplink Traffic in IEEE 802.11e Wireless LANs . In *Proc. of IEEE LANMAN*, 2005.

[18] V. A. Siris and C. Courcoubetis. Resource Control for the EDCA Mechanism in Multi-Rate IEEE 802.11e Networks. In *Proc. of IEEE Int'l Symposium on a World of Wireless, Mobile and Multimedia Networks (WoWMoM)*, 2006.

[19] G. Tan and J. Guttag. Time-based Fairness Improves Performance in Multi-rate Wireless LANs. In *Proc. of USENIX Annual Technical Conference*, 2004.

[20] I. Tinnirello and S. Choi. Temporal Fairness Provisioning in Multi-Rate Contention-Based 802.11e WLANs. In *Proc. of IEEE Int'l Symposium on a World of Wireless, Mobile and Multimedia Networks (WoWMoM)*, 2005.