Fair Access Provisioning through Contention
Parameter Adaptation in the IEEE 802.11e Infrastructure Basic Service Set †

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Abstract
We present the station-based unfair access problem among the uplink and the downlink stations in the IEEE 802.11e infrastructure Basic Service Set (BSS) when the default settings of the Enhanced Distributed Channel Access (EDCA) parameters are used. We discuss how the transport layer protocol characteristics alleviate the unfairness problem. We design a simple, practical, and standard-compliant framework to be employed at the Access Point (AP) for fair and efficient access provisioning. A dynamic measurement-based EDCA parameter adaptation block lies in the core of this framework. The proposed framework is unique in the sense that it considers the characteristic differences of Transmission Control Protocol (TCP) and User Datagram Protocol (UDP) flows and the coexistence of stations with varying bandwidth or Quality-of-Service (QoS) requirements. Via simulations, we show that our solution provides short- and long-term fair access for all stations in the uplink and downlink employing TCP and UDP flows with non-uniform packet rates in a wired-wireless heterogeneous network. In the meantime, the QoS requirements of coexisting real-time flows are also maintained.

I. INTRODUCTION

The IEEE 802.11 Wireless Local Area Network (WLAN) is built around a Basic Service Set (BSS) [1]. While a number of stations may gather to form an independent BSS with no connectivity to the wired network, the common deployment is the infrastructure BSS which includes an Access Point (AP). In the latter case, the AP provides the connection to the wired network.

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The IEEE 802.11 standard [1] defines Distributed Coordination Function (DCF) as a contention-based Medium Access Control (MAC) mechanism. The 802.11e standard [2] updates the MAC layer of the former 802.11 standard for Quality-of-Service (QoS) provisioning. In particular, the Enhanced Distributed Channel Access (EDCA) function of 802.11e is a QoS enhancement of the DCF. The EDCA scheme (similarly to DCF) uses Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) and slotted Binary Exponential Backoff (BEB) mechanism as the basic access method. The major enhancement to support QoS is that EDCA differentiates packets using different priorities and maps them to specific Access Categories (ACs) that use separate queues at a station. Each AC\textsubscript{i} within a station \((0 \leq i \leq 3)\) contends for the channel independently of the others. Levels of services are provided through different assignments of the AC-specific EDCA parameters; Contention Window (CW) sizes, Arbitration Interframe Space (AIFS) values, and Transmit Opportunity (TXOP) limits.

Both the DCF and the EDCA are defined such that each station in a BSS uses the same contention parameter set. Therefore, fair access can be achieved in the MAC layer for all the contending stations in terms of the average number of granted access opportunities, over a sufficiently long interval. However, this does not translate into achieving a fair share of bandwidth between uplink and downlink stations\(^1\) in the infrastructure BSS. An approximately equal number of accesses that an uplink AC may get is shared among all downlink flows in the same AC of the AP. This leads to the uplink/downlink unfairness problem where each individual downlink station gets comparably lower bandwidth than each individual uplink station gets at the application layer. As it will be described in detail in Section II-A, the transport layer protocol characteristics alleviate this MAC layer originated unfairness problem significantly, especially when bi-directional reliable communication is employed and/or flows with varying bandwidth requirements coexist.

We propose a novel framework which mainly consists of a measurement-based EDCA parameter adaptation block. In the proposed framework, the AP measures the network activity during periodic adaptation intervals. Then, the EDCA parameter adaptation block employs the measurement results to dynamically adapt the EDCA parameters in order to provide Weighted Fair Access (WFA) between the uplink and the downlink stations.

We present a simulation-based analysis showing the importance of the EDCA parameter selection of low priority ACs on the performance of high priority ACs (mainly on ACs using realtime flows with

\(^{1}\) In this paper, we consider the scenarios where a station only runs uplink flows or downlink flows. Therefore, each station can be named as an uplink station or a downlink station. The same labeling holds for ACs as well. We choose to present this generalization in order to keep the discussion easy to understand.
Quality-of-Service requirements). As our analysis shows, a joint CW and TXOP adaptation not only provides fair access but also does not degrade the QoS support for higher priority ACs.

A key insight of this study is that our solution considers the effects of different transport layer protocols on the design of the framework for fair access provisioning. User Datagram Protocol (UDP) and Transmission Control Protocol (TCP) are the most widely used transport layer protocols. UDP employs one-way communication. As a result, the UDP flows are nonresponsive and do not react to network congestion. As we show, the proposed WFA scheme requires an additional rate allocation block for fair UDP access in a scenario consisting of stations with different bandwidth requirements. Conversely, TCP defines reliable bi-directional communication where the backward link provides the necessary feedback for efficient rate allocation in the forward link. Although WFA is directly applicable, we show that there is a simple extension of WFA for TCP, namely Extra Prioritized Downlink Access (EPDA). The proposed EPDA scheme implicitly makes use of the TCP being bi-directional and the 802.11e MAC being fair in the uplink in order to resolve the unfair access problem.

We show that the proposed framework provides short- and long-term station-based weighted fair access both in the uplink and downlink for a wide range of scenarios. In the meantime, the QoS requirements of coexisting real-time flows are maintained. The proposed scheme is fully compliant with the 802.11e standard. It does not require any changes at the stations or the higher layer protocols of the AP.

The rest of the paper is organized as follows. We describe the unfair access problem and the related literature in Section II. We also define how we quantify fair access for the practical scenario where the bandwidth requirement of each station differs. In Section III we carry out a simulation-based analysis in order to study the side effects of the choice of best-effort traffic EDCA parameters on QoS provisioning. We describe the proposed framework in Section IV. The performance evaluation of the proposed scheme is the topic of Section V. Finally, we provide our concluding remarks in Section VI.

II. BACKGROUND

In this section, we first present the uplink/downlink unfairness problem in the IEEE 802.11e infrastructure BSS. We then provide a brief literature review on the subject. Finally, we describe how we quantify the fair access for a practical scenario where stations demanding bandwidth lower and higher than a fair per-station channel capacity coexist.
A. Problem Definition

In the 802.11e WLAN, a bandwidth asymmetry exists between contending uplink and downlink stations within a specific AC, since the AC-specific MAC layer contention parameters are all equal for the AP and the stations. If $N$ stations and an AP are always contending for the access to the wireless channel using the same AC, each host ends up having approximately $1/(N+1)$ share of the total transmissions over a long time interval. This results in $N/(N+1)$ of the transmissions to be in the uplink, while only $1/(N+1)$ of the transmissions to be in the downlink. Consequently, total bandwidth is unfairly shared between individual uplink and downlink stations, as stated previously. The uneven bandwidth share results in downlink flows experiencing significantly lower throughput and larger delay. The congestion at the AP may result in considerable packet loss depending on the size of interface buffers.

In the practical case of each downlink station having different bandwidth requirements and source packet rate, the limited bandwidth of the AP cannot even be shared in a fair manner between the downlink stations. As we will show via simulations in the sequel, the packets of a coexisting high-rate downlink flow may dominate the AP MAC buffer and the coexisting low-rate downlink flows may suffer even if their bandwidth requirement is lower than the fair share of the AP bandwidth. Therefore, a specific unfairness problem originates from the nonuniform use of the AP buffer when the AP bandwidth is limited (compared to the traffic load).

The results may even be more catastrophic in the case of TCP flows. The TCP receiver returns TCP ACK packets to the TCP transmitter in order to confirm the successful reception of data packets. In the case of multiple uplink and downlink stations in the WLAN, returning TCP ACKs of upstream TCP data are queued at the AP together with the downstream TCP data. When the bandwidth asymmetry in the forward and reverse path builds up the queue in the AP, the dropped packets impair the TCP flow and congestion control mechanisms which assume equal transmission rate both in the forward and reverse path [3]. TCP’s timeout mechanism initiates a retransmission of a data packet if it has not been acknowledged during a timeout duration. When the packet loss is severe in the AP buffer, downstream flows will experience frequent timeouts resulting in significantly low throughput. On the other hand, any received TCP ACK can cumulatively acknowledge all the data packets sent before the data packet the ACK is intended for. Therefore, upstream flows with large congestion windows will not probably experience such frequent timeouts. In this case, it is a low probability that many consecutive TCP ACK losses occur for the same flow. Conversely, flows with small congestion window (fewer packets currently on flight) may experience
frequent timeouts and decrease their congestion windows even more (note the nonuniform use of the AP buffer in this case as well). Therefore, a number of uplink stations may starve in terms of throughput while others enjoy a high throughput. This results in unfairness between individual uplink stations on top of the unfairness between the uplink and the downlink.

In order to illustrate these unfairness conditions, we carried out ns-2 simulations [4],[5] employing the default EDCA algorithm in the infrastructure BSS. We randomly picked a scenario consisting of 12 uplink and 12 downlink stations. We repeat the experiments for the cases when all the connections employ i) UDP and ii) TCP. Each connection is initiated between a separate wireless station and a separate wired station where AP is the gateway between the WLAN and the wired network. Other simulation parameters are as stated in Section V. The results are provided on the left hand side of Fig. 1 (denoted as Default). Each empty column in Fig. 1 represents the offered traffic load for the specific connection. The columns are filled up to the level of the average throughput that an individual station gets. These results illustrate, when default EDCA is used, i) there exists throughput unfairness between the uplink and the downlink stations, ii) downlink UDP stations suffer from bandwidth even if they have a lower bandwidth requirement than the fair channel access capacity, iii) there exists throughput unfairness among uplink TCP connections, and iv) data packet losses at the AP buffer almost shut down all downlink TCP connections. The results on the right hand side show the throughput obtained when the proposed algorithm, WFA, is employed. The proposed framework and the simulation results will be described in Sections IV and V respectively.

B. Related Work

The studies in the literature related to the unfair access problem discussed in this paper can be grouped into two. The first group employs queue management techniques, packet filtering schemes, or transport layer solutions without any changes in 802.11 MAC access parameters. The second group mainly proposes parameter differentiation between the AP and the stations to combat the problem.

The first group of studies mostly focuses on TCP. In [6], the effect of the AP buffer size in the wireless channel bandwidth allocation for TCP is studied. The proposed solution of [6] is to manipulate advertised receiver windows of the TCP packets at the AP. In one of our previous works, we calculated the accurate advertised receiver windows for efficient and fair TCP access for a generic WLAN scenario [7]. The uplink/downlink fairness problem is studied in [8] using per-flow queueing. A simplified approach is proposed in [9] where two separate queues for TCP data and ACKs are used. In another previous work, we proposed using congestion control and filtering techniques at the MAC layer to solve the TCP uplink
unfairness problem [10]. We extended this technique for coexisting downlink and uplink flows in [11]. Two queue management strategies are proposed in [12] to improve TCP fairness. A rate-limiter operating on the uplink traffic at the AP is proposed in [13] to provide fair access for TCP. The use of size-based scheduling policies to enforce fairness among TCP connections is proposed in [14].

The second group of studies focuses on solving the unfairness problem by contention access parameter differentiation. Distributed algorithms for achieving MAC layer fairness in 802.11 WLANs are proposed in [15], [16]. In [17], it is proposed that the AP access the channel after Point Interframe Space (PIFS) completion without any backoff when the utilization ratio drops below a threshold. On the other hand, the access based on PIFS completion does not scale for the case when there are multiple ACs at the AP, i.e., 802.11e. Achieving weighted fairness between uplink and downlink in DCF is studied through mean backoff distribution adjustment in [18]. A simulation-based analysis is carried out for a specific scenario consisting of TCP and audio flows both in the uplink and the downlink in [19] proposing AIFS and CW differentiation. As we show in this paper, sticking with static parameters may not resolve the unfairness problem at an arbitrary traffic load even if the access for AP is prioritized. An experimental study is carried out in [20] proposing mainly the use of TXOPs at the AP in order to combat TCP uplink and downlink unfairness. The use of TXOP is evaluated in [21] for temporal fairness provisioning among stations employing different physical data rates. A mechanism that suggests i) TXOP tuning (based on downlink traffic load as in [20]) for preventing delay asymmetry of real-time uplink and downlink UDP flows and ii) CW tuning for efficient channel utilization is proposed in [22]. In this paper, we show that the load-based TXOP differentiation of [20] and [22] degrades QoS support for coexisting realtime flows when these schemes are employed for fair best-effort data access provisioning. An adaptive priority control mechanism is employed in [23] to balance the uplink and downlink delay of VoIP traffic.

Our work presented in this paper falls into the second category. The key differences of our work from the previous studies are that our solution considers i) different transport layer characteristics (for UDP and TCP), ii) varying application layer bandwidth requirements among stations (not just the asymptotical case of very high load), and iii) varying network conditions over time (parameter adaptation). We also carry out an extensive analysis on the effects of EDCA parameter tuning performed at the AP on maintaining QoS requirements of coexisting real-time flows. As we will show in Section [III] the results validate our approach in this paper and in [24] for joint CW and TXOP adaptation. Note that the work presented in this paper extends our work in [24] by mainly considering the varying application layer bandwidth
requirements among stations.

C. Fairness Measure

Most of the studies in the literature quantify the fairness by employing Jain’s fairness index [25] or providing the ratio of the throughput achieved by individual or all flows in the specific directions. On the other hand, such measures have the implicit assumption of each flow or station demanding asymptotically high bandwidth (i.e., in saturation and having always a packet ready for transmission). As these measures quantify, a perfectly fair access translates into each flow or station receiving an equal bandwidth. On the other hand, in a practical scenario of stations with finite and different bandwidth requirements (i.e., some stations in nonsaturation and experiencing frequent idle times with no packets to transmit), these measures cannot directly be used to quantify the fairness of the system.

We define the fair access in a scenario where stations with different bandwidth requirements as follows.

- The stations in nonsaturation either in the uplink or the downlink (i.e., with total bandwidth requirement lower than the fair per-station channel capacity in the specific direction) receive the necessary bandwidth to serve their flows. Such stations are named as nonsaturated stations in the sequel.
- The stations in saturation either in the uplink or the downlink (i.e., with total bandwidth requirement higher than the fair per-station channel capacity in the specific direction) receive an equal bandwidth. Such stations are named as saturated stations in the sequel.

In order to quantify fair access, we propose to use the MAC queue packet loss rate for nonsaturated stations together with the comparison on channel access rate for saturated stations. Note that the latter can employ Jain’s fairness index, $f$, which is defined in [25] as follows: if there are $n$ concurrent saturated connections in the network and the throughput achieved by connection $i$ is equal to $x_i$, $1 \leq i \leq n$, then

$$f = \frac{(\sum_{i=1}^{n} x_i)^2}{n \sum_{i=1}^{n} x_i^2}.$$  \hspace{1cm} (1)

The fairness index lies between 0 and 1. Note that, in a fair scenario, every saturated station gets an equal throughput (i.e., $f = 1$) and every nonsaturated station achieves a packet loss rate of 0 at the MAC queue.

III. EDCA Parameter Analysis

The main motivation behind the design of EDCA is providing a framework where the medium access of coexisting flows can be prioritized according to their application layer traffic class. The main intention
is to provision QoS for real-time flows by prioritizing their access over best-effort and background traffic. On the other hand, as also shown in the literature, uplink/downlink unfairness problem can be combatted by the assignment of AC-specific EDCA parameters with respect to the traffic direction instead of the traffic class. In this section, we point out the fact that special care must be taken in the design of such framework so that the QoS requirements of the coexisting real-time flows can be maintained (the main intention of QoS provisioning behind the EDCA design is not jeopardized).

The solution for resolving the uplink/downlink unfairness problem using EDCA parameter differentiation is pretty clear: Prioritize the access of the given AC at the AP. This can simply be achieved by assigning the specific AC at the AP \(i)\) a lower AIFS value, \(ii)\) a lower CW, \(iii)\) a higher TXOP limit, or \(iv)\) any joint combination of these, when compared to the assigned parameters of the specific uplink AC. The challenge is to find the parameters that would provide weighted channel access while preserving QoS demands of higher priority realtime flows.

Let’s first briefly review the effects of EDCA parameter selection on the achievable uplink/downlink throughput ratio within an AC.

- Each AC can either transmit or start decrementing its backoff counter if the channel is detected to be idle for the duration of the AC-specific AIFS value [2]. This means that the access for ACs with higher AIFS values are further delayed compared to the ACs with lower AIFS values every time the channel becomes busy. At low channel load, the effect of AIFS on prioritization is not significant, since the backoff countdown is not frequently interrupted by other transmissions. Conversely, at high channel load, AIFS prioritization becomes a significant factor. Every time the channel is grabbed, this directly means a further delay on the stations with lower priority (i.e., larger AIFS) when compared to the stations with higher priority.

- The stations pick a backoff value uniformly distributed between 0 and the current CW size and complete a backoff countdown before transmission [2]. Upon gaining access to the medium, each AC may carry out multiple frame exchange sequences as long as the total access duration does not go over its TXOP limit [2]. The channel access ratio between uplink and downlink within an AC varies almost linearly with respect to the selection of \(CW_{min}[3]\) and \(TXOP\) values in asymptotical

\(^2\)The 802.11e standard suggests the use of an admission control algorithm for QoS provisioning. In an ideal scenario, the admission control algorithm prevents the access of a real-time station if its admittance to the network can degrade the overall QoS. This also means that, in an ideal scenario, QoS is preserved, all real-time stations are nonsaturated, and unfairness problem does not exist for QoS stations. Therefore, in this paper, we consider the best-effort traffic that no admission control is or can be applied.

\(^3\)As [2] defines, the initial value of AC-specific CW is \(CW_{min}\). At every retransmission the CW is doubled, up to \(CW_{max}\).
conditions (saturation). Following our analytical calculation in [24], the approximate channel access ratio $U_{i,u/i,d}$ between uplink and downlink within AC$_i$, namely AC$_{i,u}$ and AC$_{i,d}$, can be calculated as

$$U_{i,u/i,d} \approx \frac{CW_{\text{min},i,d} N_{\text{TXOP},i,u}}{CW_{\text{min},i,u} N_{\text{TXOP},i,d}}$$

(2)

when AIFS$_{i,u} = \text{AIFS}_{i,d}$ and both directions are saturated. Note that $N_{\text{TXOP}}$ denotes the maximum number of packets that AC$_i$ can fit into one TXOP.

Simply by using (2), we can calculate a set of $CW_{\text{min}}$ and TXOP values for AC$_{i,d}$ that would approximately achieve a predetermined throughput ratio $U_{i,u/i,d}$ for given $CW_{\text{min}}$ and TXOP values of AC$_{i,u}$, and vice versa. On the other hand, the throughput ratio achieved by AIFS differentiation is yet to be approximated via a simple linear relationship as it can be done in (2) for CW and TXOP. Therefore, in this work, we consider joint CW and TXOP differentiation in provisioning weighted fair access. AIFS differentiation is only used between ACs to provide prioritization between realtime and best-effort flows.

We carried out a simulation-based analysis to further analyze the effects of CW and TXOP differentiation on both fair access and QoS provisioning. We consider a scenario with two active ACs. For both ACs, we use a traffic model with Poisson packet arrivals. The transport layer protocol is UDP for both ACs. We use 11 Mbps 802.11b PHY and assume that the wireless channel is errorless.

The high priority traffic uses AC$_3$ with EDCA parameters $AIFS = 2$, $CW_{\text{min}} = 7$, $CW_{\text{max}} = 15$, $TXOP = 1.504$ ms both at the AP and the stations (as suggested in [2]). We consider 5 uplink and 5 downlink high priority flows generated at 250 kbps. We intentionally do not saturate the high priority AC, so that the lower priority ACs do not starve and the effects of CW and TXOP selection can be observed. This also corresponds to a practical scenario since the traffic load should be well controlled and an admission control algorithm should keep the high priority AC nonsaturated to support parameterized QoS [26], [27].

The low priority AC is considered to be serving best-effort traffic. We set the traffic load so high that the low prority AC is saturated both at the stations and the AP. This is also a valid assumption to analyze the worst-case scenario, since no admission control is applied for best-effort traffic category in practice. We consider four different cases in assigning the EDCA parameters of the AP and the stations for the low priority traffic.

- **Default:** Both the AP and the stations use the same parameters which are tentatively set as $AIFS = 3$, $CW_{\text{min}} = 31$, $CW_{\text{max}} = 511$, $TXOP = 0$. 
• TXOP differentiation: The AP is assigned a TXOP regarding the total number of downlink flows $n_d$, i.e., $TXOP = n_d \cdot T_{exc}$, where $T_{exc}$ is the time required to complete a data frame exchange (including MAC/PHY overhead). Note that this is similar to the approach proposed in [20], [22].

• CW differentiation: The AP is assigned a smaller $CW_{min} = 7$. The stations are assigned a $CW_{min}$ regarding the total number of downlink flows $CW_{min} = 7 \cdot n_d$.

• Joint CW and TXOP adaptation: We employ our joint adaptation approach, WFA, as proposed in this paper in the sequel.

Note that in the last three cases, the parameters are set so that a utilization ration of 1 between uplink and downlink can be approximately achieved.

Fig. 2 and Fig. 3 show the fairness index and the total throughput for the best-effort AC, respectively. Fig. 4 and Fig. 5 show the average delay and the average jitter experienced by QoS flows for increasing number of low priority uplink and downlink stations, respectively. We can extract the following insights from the presented simulation-based analysis.

• As shown in Fig. 2 static CW and TXOP differentiation cannot maintain fair access as a result of the fact that the channel access ratio as calculated by (2) is only an approximation. The design of an analytical model which captures all network details in order to calculate the exact parameters is hard and complex. Dynamic adaptation as proposed in this paper simply preserves weighted fair access.

• As shown in Fig. 3 when compared to the default case, both TXOP differentiation and CW differentiation improve channel utilization. In the former case, channel contention overhead is decreased by the use of TXOP. In the latter case, the stations are assigned larger $CW_{min}$ values so that the collision overhead is decreased while the downlink enjoys a higher channel access rate with the assigned smaller $CW_{min}$ value.

• As shown in Fig. 4 as the number of best-effort flows increases, employing TXOP differentiation at the AP for low priority traffic jeopardizes the QoS of high priority flows (the average delay increases exponentially). If a packet belonging to a QoS flow arrives while the channel is busy because of a best-effort transmission, the QoS packet has to wait a long time until the transmission is completed. On the other hand, in the case of CW differentiation, when best-effort flows access the channel, they hold the channel for a much shorter duration at every access which means a smaller access overhead for the QoS stations.

• A smaller CW selection at the AP for low priority flows does not degrade QoS of higher priority
flows in the same order of TXOP differentiation. In the specific scenario, the downlink best-effort flows use the same $CW_{\text{min}}$ as the QoS flows are assigned. The differentiation is still maintained via different AIFS values. Moreover, the access frequency for the stations are decreased since they use larger CW values (compared to the default EDCA and TXOP differentiation cases). Conversely, the total throughput for the best-effort traffic increases (due to lower collision overhead) and the QoS stations experience a low packet delay.

- A similar discussion as for delay holds on the jitter of QoS flows as per the results presented in Fig. 5.

Fig. 6-9 show the results when best-effort flows employ TCP. As can be seen from Fig. 7-9, similar discussions on the comparison hold for throughput of the best effort flows, delay and jitter experienced by QoS flows. However, as shown in Fig. 6, both TXOP differentiation and CW differentiation provide fair access among TCP flows (different than UDP). These schemes implicitly make use of the results of capture effect in fair access provisioning. As a result of capture effect, the EDCA parameters settings favors the downlink access in both CW differentiation and TXOP differentiation. As the results present, while this causes unfair access between uplink and downlink UDP flows, fair medium access is still maintained among TCP flows (when TCP does not employ the delayed ACK mechanism). The reasoning behind this behavior is actually what motivates the design of proposed EPDA algorithm in the sequel and will be described in detail in Section IV-E.

Similar discussions hold when the stations use 54 Mbps 802.11g PHY layer as presented in Fig. 10-17.

This analysis motivates the joint use of CW and TXOP differentiation for efficient and fair medium access. A multiple packet exchange in a TXOP improves channel utilization by decreasing contention overhead. On the other hand, as our analysis implies, the TXOP limit assigned should not go over a threshold for concurrent fair access and QoS provisioning. Although we provide the results for the proposed WFA scheme in Fig. 2-4, we provide the discussion on WFA performance in Section V after the framework is described in Section IV.

IV. A FRAMEWORK FOR FAIR ACCESS PROVISIONING

An EDCA parameter adaptation block lies in the core of the proposed framework. The adaptation block employs the basic idea of prioritizing the access of the AP so that the uplink/downlink unfairness problem can be resolved. The adaptation block employs a novel joint CW and TXOP differentiation scheme in order to provide weighted fair access within an AC while preserving QoS of coexisting realtime flows.
The proposed EDCA parameter adaptation procedure has two main phases; \textit{i)} network activity measurement during an adaptation interval and \textit{ii)} dynamic parameter adaptation. As previously stated, we design this scheme for Weighted Fair Access provisioning, therefore name as WFA.

\textbf{A. Network Activity Measurement during an Adaptation Interval}

The AP measures the network activity for $\beta$ beacon intervals which we define as an adaptation interval. At the end of each adaptation interval, the EDCA parameters are adapted regarding measurement results as described in the sequel.

During the adaptation interval, the AP scans for the unique source and destination MAC addresses observed both in the uplink and the downlink to estimate the number of active uplink and downlink stations, $n_u$ and $n_d$, respectively. For each station in the downlink, it uses exponential moving averaging\footnote{The formula for calculating an exponential moving average is $x_t = \delta y_{t-1} + (1 - \delta)x_{t-1}$, where $y_t$ is the observation during the last time interval $(t-1, t)$, $x_t$ is the moving average for all observations until at time $t$, and $\delta$ is the constant smoothing factor ($0 \leq \delta \leq 1$).} in order to calculate the average number of packets received for transmission and the number of packets successfully transmitted during an adaptation interval. For each station in the uplink, it also uses exponential moving averaging in order to calculate the average number of packets successfully received in the wireless link (i.e., the average number of packets an uplink station transmits successfully) during an adaptation interval.

\textbf{B. Dynamic Parameter Adaptation}

If a new station is detected to be starting transmission or an existing station is detected to be concluding transmission in the last adaptation interval, in the dynamic parameter adaptation phase, mainly an EDCA parameter decision procedure is completed employing simple and approximate analytical calculations. Otherwise, the dynamic parameter adaptation phase handles the fine tuning on the $CW_{\text{min}}$ and $TXOP$ values. Our motivation behind distinguishing these two cases is to improve the convergence rate of the parameter tuning (e.g., in case an abrupt change is needed in EDCA parameters due to several flows starting/stopping transmission in the last adaptation interval). A good initial guess also enables carrying out the tuning on the parameters in smaller steps (i.e., fine tuning) which enhances the stability of the parameter adaptation.

\textit{a) Parameter Decision:} In a saturated scenario, a good guess on the appropriate EDCA parameter settings that would approximately achieve a predetermined channel access ratio between uplink and downlink can be made using the total number of downlink stations [24].
In this paper, we improve our previous work [24] by releasing the assumption of every station being in saturation. As described in Section II-C, a fair scenario with each station having an equal weight in terms of medium access corresponds to nonsaturated stations being served with no packet losses at the MAC queue and the saturated stations sharing the rest of the bandwidth equally. In such a case, the ratio of the total fair bandwidth of the AP to the total fair bandwidth of a saturated station for the specific AC cannot be determined directly from the total number of stations. We introduce the concept of effective number of downlink stations using AC$_i$, $e_{i,d}$, in order to quantify this ratio approximately. The value of $e_{i,d}$ corresponds to an approximate number of saturated stations that would consume an approximately equal bandwidth as the AP consumes in a fair scenario. Due to characteristic differences of UDP and TCP, the calculation for $e_{i,d}$ is transport protocol dependent as will be described individually in Sections IV-C and IV-D.

Let $U_i$ be the target utilization ratio between saturated uplink and downlink stations using AC$_i$. Then, in case a change in $n_u$ or $n_d$ is detected, we make the parameter decision as follows.

- Using the linear relationship in (2), a set of possible $CW_{min,i}$ values for the AP is calculated using

\[ CW_{min,i,d} = \frac{CW_{min,i,u} \cdot N_{TXOP,i,u}}{e_{i,d} \cdot U_i \cdot N_{TXOP,i,d}} \] (3)

for varying $N_{TXOP,i,d}$ values from 1 to a threshold, $N_{TXOP,thresh}$. Note that $CW_{min,i,u}$ and $TXOP_{i,u}$ are used as they were assigned in the previous adaptation interval.

- The calculated $CW_{min,i}$ values that are not integers are rounded to the closest integer value. We have quantified the effect of rounding on uplink/downlink access ratio and have defined a simple extension of the BEB algorithm which can be employed for non-integer CW values in [28]. In this paper, we opt out using this extension.

- The decision on the $CW_{min,i}$-$TXOP_{i}$ pair is made by ensuring that $CW_{min}$ of a low priority AC (at the AP or a station) is not smaller than $CW_{min}$ of any higher priority AC. If any $CW_{min}$-$TXOP$ pair does not satisfy this simple prioritization rule, we double $CW_{min,i}$ (and therefore $CW_{max,i}$) of the station, and complete another round of calculation to decide on a new set. This process continues until a decision is made. Although the results in this paper are presented for the cases which prefer the pair with the $N_{TXOP,i,d}$ value is at least 2 (for decreased contention overhead) and $CW_{min,i,u}$

5Note that we define a target utilization ratio between saturated uplink and downlink stations. In a fair scenario, the nonsaturated stations receive the bandwidth they demand and are not subject to any weight.

6$CW_{min,i}$ and $TXOP_{i}$ of the stations are initialized to the values suggested in [2] in the very first adaptation phase.
is at most $\theta = 4$ times the default $CW_{min,i,u}$ suggested in [2] (for preventing very large $CW_{min,i,u}$ assignments so that the stations do not suffer from bandwidth), the performance difference is observed to be marginal for other selection schemes (preferring the pair with $N_{TXOP_i,d} = N_{TXOP,thresh}$, random selection, etc.).

Every beacon interval, the AP announces the values of the AC-specific EDCA parameters to the stations. The stations overwrite their EDCA parameter settings with the new values if any change is detected. Due to the specific design of the EDCA Parameter Set element in the beacon packet, the stations can only employ $CW$ values that are integer powers of 2, i.e., the AP encodes the corresponding 4-bit fields of $CW_{min}$ and $CW_{max}$ in an exponent form. The proposed method initializes $CW$ parameters of the stations to default values and uses exponents of 2 if an increase is needed. Therefore, it is compliant to the standard. A key point which the studies in the literature have not considered is that the $CW$ settings of the ACs at the AP are not restricted to the powers of 2. The proposed scheme releases this restriction being employed at the AP in the studies in the literature [22]. The absence of this restriction provides flexibility on weighted fair access provisioning, where the AP uses any $CW$ value in order to achieve an arbitrary uplink/downlink utilization ratio.

$b)$ Parameter Tuning: Let $U_{i,m}$ be the measured utilization ratio during the last adaptation interval and $U_{i,r}$ be the required utilization ratio between uplink and downlink saturated stations using $AC_i$. The parameter tuning is done as follows ($0 \leq \gamma \leq \alpha \leq 1$, $\chi_{high} > 0$, and $\chi_{low} > 0$):

- If $U_{i,m} < (1 - \gamma)U_{i,r}$, then $CW_{min,i,d}$ is decreased by $\chi_{high}$.
- If $U_{i,m} < (1 - \alpha)U_{i,r}$, then $CW_{min,i,d}$ is decreased by $\chi_{low}$.
- If $U_{i,m} > (1 - \gamma)U_{i,r}$, then $CW_{min,i,d}$ is increased by $\chi_{high}$.
- If $U_{i,m} > (1 - \alpha)U_{i,r}$, then $CW_{min,i,d}$ is increased by $\chi_{low}$.
- Otherwise, no action is taken.

Employing the previously stated prioritization rule, if $CW_{min,i,d}$ gets smaller than the $CW$ of an AC that is higher priority, we can take two alternative actions.

- Double both $CW_{min,i,u}$ and $CW_{min,i,d}$.
- Double both $CW_{min,i,d}$ and $TXOP_{i,d}$ (if and only if new $N_{TXOP_i,d} < N_{TXOP,thresh}$).

Note that both of these actions are expected to maintain the channel access ratio approximately at the same level since the ratio in (2) can be preserved. In the simulations presented in this paper, we prefer

\footnote{Note that $\chi_{high}$ and $\chi_{low}$ can take any value since $CW_{min,i,d}$ is not restricted to be an exponent of 2.}
the former unless $CW_{min,i,u}$ is $\theta = 4$ times the default $CW_{min,i,u}$ suggested in [2]. We observed that the performance differs marginally even when another scheme is employed such as $\theta$ is assigned another value or the latter of the two alternative actions is preferred.

As shown in Section II-A, the interactions of the transport layer protocol and the 802.11 medium access layer protocol play an important role in how the channel access opportunities are shared between the contending stations. The most effective difference is that while UDP uses one-way unreliable communication, TCP defines a backward ACK link for rate allocation and reliable data delivery. Leaving the core of the fair access provisioning algorithm as described previously in this section, our design considers these characteristic differences by introducing additional functional blocks as necessary.

C. WFA for UDP

1) Effective number of downlink UDP stations: The effective number of downlink UDP stations mainly depends on the number of saturated and nonsaturated downlink stations. Therefore, the AP needs to figure out the state of each station (i.e., whether it is saturated or nonsaturated). The AP measures the total channel capacity for $AC_i$, $C_i$, in terms of total average number of successful transmissions during an adaptation interval (using exponential averaging over successive adaptation intervals). Then, the algorithm we use in estimating the effective number of downlink UDP stations is as follows.

1) The initial per-station fair channel access capacity is calculated as $C_{f,i} = C_i/n_i$ where $n_i$ is the total number of active uplink and downlink stations using $AC_i$ (whether saturated or nonsaturated).
2) The saturated stations in the uplink achieve an approximately equal channel access rate as they are employing the same set of EDCA parameters. Therefore, the uplink stations that achieve an average channel access rate within a range of the highest measured per-station channel access rate are labeled as saturated.
3) We label each unlabeled station as running in saturation or nonsaturation based on the fair channel capacity $C_{f,i}$. A downlink (uplink) station is labeled saturated if its measured packet arrival rate to the AP from the wired link (from the wireless link) is higher than $C_{f,i}$. All remaining stations are labeled nonsaturated.
4) Since the nonsaturated stations require lower bandwidth than $C_{f,i}$, the per-station channel capacity for saturated stations can be recalculated as

$$C_{f,i} = \frac{C_i - C_{i,nonsat}}{n_{i,sat}}$$ (4)
where $C_{i,nonsat}$ is the total channel capacity needed for serving nonsaturated stations using AC$_i$ and $n_{i,sat}$ is the number of stations labeled as saturated.

5) The labeling procedure in step 3 is repeated. If the previous label of at least one station is changed in step 3, the iterations continue. Otherwise, the most recent calculated $C_{f,i}$ is an estimation on the per-station fair share for saturated stations.

Then, the effective number of downlink UDP stations using AC$_i$, $e_{i,d}$, can simply be calculated as

$$e_{i,d} = \frac{C_{i,nonsat,d} + n_{i,sat,d} \cdot C_{f,i}}{C_{f,i}}.$$

(5)

where $C_{i,nonsat,d}$ is the total channel capacity needed for serving nonsaturated downlink stations using AC$_i$ and $n_{i,sat,d}$ is the number of downlink stations labeled as saturated.

2) Fair Rate Allocation (FRA): As previously described in Section II-A, if saturated and nonsaturated downlink stations coexist, nonsaturated stations suffer from significant packet losses although they require a bandwidth smaller than the per-station fair channel access capacity. Even when the uplink/downlink fairness problem is resolved via the proposed EDCA parameter adaptation scheme, this problem persists if there is at least one saturated station in the downlink. We introduce an FRA block on top of the AP MAC queue which is essentially a packet filter (or a token bucket filter). If a downlink station is detected to be consuming bandwidth higher than the fair channel access rate $C_{f,i}$, the packets arriving at the rate higher than the fair access rate are dropped from the queue. This opens up the buffer space for nonsaturated stations which can achieve their demanded bandwidth.

The packet drop probability $p_{d,i,j}$ for saturated downlink station $j$ using AC$_i$ is calculated simply as follows.

$$p_{d,i,j} = \frac{A_{i,j} - C_{f,i}}{A_{i,j}}$$

(6)

where $A_{i,j}$ is the average packet arrival rate for the corresponding downlink station. Note that $p_{d,i,j}$ adapts to $C_{f,i}$ changes as a result of EDCA parameter adaptation.

The UDP results presented in this paper for the proposed WFA scheme employs the proposed FRA block at the AP.

D. WFA for TCP

1) Effective number of downlink TCP stations: As TCP data rate in the forward link depends on TCP ACK rate in the backward link and is adjusted according to network congestion, it is hard to estimate
whether a TCP flow is saturated or not at the AP. Therefore, the measurement-based estimation algorithm in Section IV-C.1 may not always be applicable.

As the TCP ACK traffic of uplink stations traverses the AP in downlink, the downlink TCP bandwidth also depends on the number of uplink TCP stations. Let every $b$ TCP data be acknowledged with one TCP ACK. Then, define

$$\eta_{i,d} = n_{i,d} + \frac{n_{i,u}}{b}.$$  

(7)

As we have also confirmed via simulations, if we directly employ (7) in (3) directly as the number of effective downlink stations, the initial parameter guess is usually far from the correct parameter setting that would provide weighted fair access in scenarios nonsaturated stations exist. This is because the effective number of TCP stations as calculated by (7) implicitly assumes that every station to be saturated. This makes parameter tuning phase unstable and converge in a longer duration.

To improve the stability of parameter tuning, we linearly normalize $\eta_{i,d}$ according to the most recent contention parameters and the corresponding measured number of flows (as denoted with superscript $p$ in (8)) in the calculation of the effective number of downlink TCP flows.

$$e_{i,d} = \frac{C_{W_{min,i,u}}^p \cdot \eta_{i,d}}{C_{W_{min,i,d}}^p \cdot \eta_{i,d}^p}.$$  

(8)

As it can be seen by employing (8) in (3), setting $e_{i,d}$ as in (8) enables the use of the already converged contention parameters as a basis for calculating the new parameters. As also observed via simulations, this approach improves the convergence properties of parameter tuning for TCP (or in a generic case when it is hard to classify stations as saturated and nonsaturated).

E. Extra Prioritized Downlink Access (EPDA) for TCP

We also propose an alternative and practical solution for TCP fairness provisioning: Provide the AP Extra Prioritized Downlink Access (EPDA) opportunity, so that the corresponding AC queues of the TCP flows always remain nonsaturated at the AP. The reasoning behind this novel idea is two-fold; $i$) this avoids the TCP packet drops at the AP which is the main cause for unfairness as shown in Section II-A, and $ii$) such an approach makes the fairness provisioning rely only on the uplink access and 802.11 MAC is fair to all competing uplink stations (given that there are no packet losses at the AP). Note that although this can result in making the non-AP stations saturated, no buffer overflow is actually observed due to

\footnote{A typical value for $b$ is 2. When $b > 1$, it is called delayed TCP ACK mechanism.}
our practical assumption that TCP congestion windows are set regarding the available buffer space at the TCP senders and receivers. As the slow link limits the throughput for all TCP stations (in this case, the slow link is the upstream data link for uplink TCP stations and the upstream TCP ACK link for downlink TCP stations) and 802.11 MAC provides fair access to all uplink stations, uplink/downlink unfair access problem can simply be resolved.

When the delayed TCP ACK mechanism is used, the proposed EPDA scheme prioritizes the downlink stations over uplink stations. As previously mentioned, the upstream access is fairly distributed among upstream data link of uplink stations and the upstream TCP ACK link of downlink stations. On the other hand, every one upstream TCP ACK stands for $b$ data packets. Since the AP queues are nonsaturated, the saturated downlink TCP stations enjoy $b$ times higher data packet transmissions than the saturated uplink stations can transmit over a sufficiently long interval. Therefore, the channel utilization ratio $U$ in EPDA is determined by TCP data-to-ack ratio, $b$. Note that in an 802.11e infrastructure BSS, it is highly probable that the downlink load will be significantly higher than the uplink load. Therefore, maintaining a downlink to uplink access ratio $U > 1$ can also be practical.

The EDCA parameter adaptation block uses the queue size as an indication for dynamically adapting the parameters in EPDA scheme. Therefore, the dynamic parameter tuning rules differ from WFA and is as follows.

- If average AP queue size in an adaptation interval is larger than a threshold value, $q_{thresh}$, then $CW_{min,i,d}$ is decreased by $\chi_{low}$.
- If average AP queue size stays under the threshold value, $q_{thresh}$, then $CW_{min,i,d}$ is increased by $\chi_{low}$.
- Otherwise, no action is taken.

In simulations, we observed that doubling the EDCA TXOP (the value calculated in the parameter decision phase) for the specific AC at the AP is sufficient to enable the proposed EPDA scheme. Although we used larger EDCA TXOP size in the simulations presented in this paper, using smaller CW values is also applicable. Note that the EDCA parameter settings for the EPDA scheme is also up to the previously stated rules that need to be employed in order to maintain differentiation among different ACs and QoS support for real-time stations.
V. Simulation Results

We carried out simulations in ns-2 [4,5] in order to evaluate the performance of the proposed algorithms. We consider a network topology where each wireless station initiates a connection with a wired station and the traffic is relayed to/from the wired network through the AP. The data connections use either UDP or TCP NewReno. The UDP connections employ the traffic model with exponentially distributed packet interarrival times. The TCP traffic either uses a File Transfer Protocol (FTP) agent, which models bulk data transfer or a Telnet agent, which simulates the behaviour of a user with a terminal emulator or web browser. In the experiments, saturated TCP stations employ FTP and nonsaturated TCP stations use Telnet agents. Unless otherwise stated, the flows are considered to be lasting the simulation duration. In some experiments, short flows are used which simulate a fixed size data transfer and leave the system after all the data is transferred. The default TCP NewReno parameters in ns-2 are used.

The UDP and TCP flows are mapped to AC$_1$ and AC$_0$, respectively, where the initial EDCA parameters are $AIFS_0 = AIFS_1 = 3$, $CW_{min,0} = CW_{min,1} = 31$, $CW_{max,0} = CW_{max,1} = 511$, $TXOP_0 = TXOP_1 = 0$. These access parameters are selected arbitrarily (the unfairness problem exists regardless of the selection if AP and the stations use equal values). All the stations are assumed to have 802.11g PHY using 54 Mbps and 6 Mbps as the data and basic rate respectively [29] while wired link data rate is 100 Mbps. The packet size is 1500 bytes for all flows. The buffer size at the stations and the AP is set to 100 packets per AC. The receiver advertised congestion window limits are set to 42 packets for each flow. Note that the scale on the buffer size and TCP congestion window limit are inherited from [6]. Although the current practical limits may be larger for congestion windows and smaller for buffer sizes, the unfairness problem exists as long as the ratio of buffer size to congestion window limit is not arbitrarily large (which is not the case in practice). The beacon interval is 100 ms. We found $\beta = 10$, $\alpha = 0.05$, $\gamma = 0.25$, $\chi_{high} = 5$, and $\chi_{low} = 1$ to be appropriate through extensive simulations.

Wireless channel is assumed to be an Additive White Gaussian Noise (AWGN) channel. On top of the energy-based PHY model of ns-2, we implemented a BER-based PHY model according to the framework presented in [30] using the way of realization in [31]. Our model considers the channel noise power in Signal-to-Noise Ratio (SNR) [5]. A packet is detected at the receiver if the received power is over a specified threshold. Then, the packet error probability is calculated using the theoretical model presented in [30] regarding the channel SNR, the modulation type used for the transmission of the packet, and the packet size. If a randomly drawn number is higher than the calculated probability, the packet is assumed
to be received correctly, otherwise the packet is labelled as erroneously decoded, and discarded. We set wireless channel noise levels such that each station experiences a finite packet error rate (PER). We repeat the tests for the AWGN channel SNR values when PER is 0%, 0.1% or 1% for UDP and TCP data packets.

We set the required utilization ratio $U_{i,r} = 1$ as in all of the previous studies in the literature.

**a) Scenario 1 - Problem Definition:** We repeated the same set of experiments as described for the default case in Section II-A. As the results on the right hand side of Fig. 1 show, WFA provides fair access for both UDP and TCP in the case of coexisting flows with different bandwidth requirements. Fitting perfectly to the fair access definition in Section II-C the nonsaturated stations achieve the bandwidth they demand, while the saturated stations achieve an equal bandwidth for both UDP and TCP scenarios.

**b) Scenario 2 - Varying Number of Flows over Time / Adaptation Stability:** We tested the performance of WFA and EPDA when the number of active stations vary over time. The experiments are repeated for the cases when all the stations either employ UDP or TCP without delayed ACKs. The presented results are for the errorless channel.

Fig. 18 shows the instantaneous throughput of each UDP station achieves with respect to time. Initially, there are 2 uplink and 2 downlink stations, one in each direction has a packet rate of 10 Mbps, and the other has a packet rate of 0.5 Mbps. Over the course of the simulation, 4 uplink and 4 downlink stations (with packet rates of either 20 Mbps or 1 Mbps) initiate connections at different times, stay active for 15 seconds, and leave the system. As the results present, fair access is always maintained when the number of active connections vary over time. Every time a saturated UDP uplink or downlink station joins the network, the bandwidth is fairly shared. The nonsaturated uplink and downlink stations do not suffer from scarce bandwidth (while they coexist with saturated stations).

Fig. 19 and Fig. 20 show the results when stations use TCP, and WFA and EPDA is employed, respectively. Initially, there are 2 uplink and 2 downlink stations, one in each direction employs an FTP agent and the other employs a Telnet agent with a packet rate of 0.5 Mbps. Over time, 4 uplink and 4 downlink stations (FTP or Telnet) initiate connections at different times. FTP stations leave the system after a total of 6000 packets are transferred (which approximately lasts around 15 seconds for the specific scenario). Telnet stations have a packet rate of 1 Mbps and leave after 15 seconds. As the results present, fair share of the bandwidth is always maintained among TCP stations.

We present the results for the same scenarios in Fig. 21 and Fig. 22 when the delayed TCP ACK mechanism is enabled. WFA can maintain fair access between uplink and downlink as the EDCA parameters
are adapted accordingly. On the other hand, as previously mentioned in Section IV-E, downlink access is favored in EPDA due to the use of delayed TCP ACKs. In EPDA, the AP has prioritized access and is no more the bottleneck. The upstream access is fairly distributed among upstream data link of uplink stations and the upstream TCP ACK link of downlink stations. As every one upstream TCP ACK stands for $b = 2$ data packets in the specific scenario, downlink stations enjoy a comparably higher bandwidth. EPDA resolves the critical unfairness problem (In Default scenario, just a few upload flows can sustain high throughput as discussed in Section II-A). The weight between the uplink and the downlink depends on the TCP data-to-ack ratio.

Fig. 23-27 show the instantaneous $CW_{\text{min}}$ and $N_{\text{TXOP}}$ values used at the AP and the stations over the course of simulation for the same scenarios as described above. Note that the parameter adaptation block selects the initial TXOP values to be equal to $2 \cdot T_{\text{exe}}$ in the downlink and 0 in the uplink. As the results show, the parameter adaptation is stable and converges pretty quickly in all scenarios. As the flows start or stop, we see bumps in assigned EDCA parameters (parameter decision phase). If needed fine tuning further adapts parameters at the end of following adaptation intervals. The simulation results show no unstable behavior in the dynamic adaptation of parameters over a wide range of scenarios.

c) Scenario 3 - Increasing Number of Stations: We tested the performance of WFA for increasing number of stations when all the stations have i) UDP or ii) TCP connections. We also report the performance of EPDA for the case of TCP. For the specific scenario, half of the UDP stations in each direction generate packets at 10 Mbps and the other half has different packet rates selected between 150 Kbps and 550 Kbps (as in Scenario 1). For TCP, half of the stations use the FTP agent, while the other half use the Telnet agent with packet rates between 150 Kbps and 550 Kbps. Unless otherwise stated, TCP receivers employ the delayed TCP ACK mechanism.

Fig. 28 and Fig. 29 compares the performance in terms of fair access and total throughput for default EDCA and WFA for increasing number of UDP stations in each direction, respectively. In, Fig. 28 the right y-axis denotes the fairness index, $f$, among the saturated stations, while the left y-axis denotes the average Packet Loss Rate (PLR) for nonsaturated stations. As the results present, the proposed WFA scheme can provide fair access (i.e., $f = 1$ and $PLR = 0$) irrespective of the number of stations. As Fig. 29 shows, high channel utilization is also maintained.

We repeated the same scenario for TCP stations. Fig. 30 and Fig. 31 compare the performance in

9 A TXOP duration equal to 0 means that the specific AC can only transmit 1 packet per channel access [2].
terms of fair access and total throughput for default EDCA, WFA, and EPDA for increasing number of TCP stations in each direction, respectively. Both WFA and EPDA schemes resolve the uplink/downlink unfairness problem. As described in Section IV-E the downlink achieves higher channel access share in EPDA when TCP delayed ACK scheme is used. That’s why the fairness index is $f = 0.9$ for EPDA.

The same set of experiments are repeated when PER is set to 0.1% and 1% in the wireless channel. Fig. 32-39 present the corresponding results. The effects of wireless channel errors are marginal on the average throughput and fairness performance as the MAC level retransmissions efficiently combats wireless channel losses. The discussion on the performance comparison of default EDCA, WFA, and EPDA remains similar even when the wireless is not error-free.

When TCP receivers do not employ delayed TCP ACK mechanism, both WFA and EDPA provides fair uplink and downlink access as presented in Fig. 40. The performance comparison for the same scenario is provided in Fig. 41.

d) Scenario 4 - Short Flows: We tested the performance of WFA and EPDA in case short TCP connections are made when there are ongoing bulk TCP transfers both in the uplink and downlink. In this specific scenario, we have 15 uplink and 15 downlink TCP stations where 10 of them in both directions generate short TCP connections at arbitrarily selected times. Each short TCP connection has a total of 30 packets to send and leave the system when the transaction is completed. The remaining 5 connections in each direction last for the whole simulation duration.

Fig. 42 shows the total transmission duration for individual short TCP connections for the default EDCA, the proposed WFA, and EPDA schemes. Note that flow indices from 1 to 10 represent uplink TCP connections while flow indices from 11 to 20 represent downlink TCP connections. The short file transfers can be completed in a considerably shorter time compared to default EDCA when the proposed framework is used. Although not explicitly presented, most of the downlink short TCP connections experience connection timeouts and even cannot complete the whole 30 packet transaction within the simulation duration when the default algorithm is used. As expected, EPDA outperforms WFA by avoiding comparably longer packet delays at the AP buffer. These results also indicate that the proposed schemes are short-term fair.

e) Scenario 5 - Coexisting Realtime Flows: The specific simulation scenario is previously described in Section III. The average delay that realtime connections experience are evaluated in Fig. 4. The results clearly indicate that as the number of best-effort flows increases, fair access can be achieved at the expense
of a significant degradation of QoS support for high priority flows if only TXOP differentiation is used. Note that this idea is employed in [20],[22]. Among the compared schemes, WFA is the only one that provides fair access together with high channel utilization and marginal degradations on QoS provisioning.

f) Scenario 6 - Varying Number of Flows among Stations: We tested the performance of the proposed algorithms when there are varying number of i) UDP or ii) TCP connections at an uplink or a downlink station. In this specific scenario, we assume all the best effort flows to be in saturated state. We repeated the tests for different number of stations in the network where one third of the stations have 1 connection, the other one third of the stations have 2 connections and the remaining stations have 3 connections. The total number of uplink and downlink stations is equal.

Fig. 43 shows the fairness index among per-station access bandwidth when the best-effort flows employ UDP. Similarly, Fig. 44 shows the fairness index among stations for TCP (when the delayed ACK mechanism is disabled). As the results clearly present, the proposed methods provide perfect fairness independently of the number of active flows at a station.

Fig. 45 and Fig. 46 show the total throughput of the stations when the best effort flows use UDP and TCP, respectively. As it can be seen from Fig. 45, the proposed WFA algorithm achieves a higher throughput than the default algorithm as a result of higher TXOP values used at the AP and higher CW values at STAs (fewer collisions occur when the number of stations increases). However, this is not the case for TCP flows, as only a few flows share the whole bandwidth in the default scenario (all of the downlink TCP flows and some of the uplink TCP flows are totally shut down due to the reasons as described in Section II-A), they can increase their congestion windows comparably to larger values on the average (higher throughput) and there are fewer stations contending for access (fewer collisions). Although the default scheme may obtain a higher bandwidth utilization than the proposed algorithms, it still fails to provision fair access as shown in Fig. 44.

g) Scenario 7 - Varying TCP Congestion Windows: In this scenario, we generate TCP connections with receiver advertised congestion window sizes of 12, 20, 42, or 84. We vary the number of FTP connections from 4 to 24 and the wired link delay from 0 to 50 ms. For each scenario, the number of flows using a specific congestion window size is uniformly distributed among the connections (i.e., when there are 12 upload and 12 download TCP flows, 3 of the upload/download TCP connections use the congestion window size $W$, where $W$ is selected from the set $S = 12, 20, 42, 84$). The wireless channel is assumed to be errorless. The TCP delayed ACK mechanism is enabled.
Fig. 47 shows the fairness index among all connections. We compare the default DCF results with the results obtained when the AP employs the proposed WFA scheme. As the results imply, with the introduction of the proposed control block at the AP, a better fair resource allocation can be achieved. However, a perfect fairness is not observed when the link delay is higher and the number of flows is lower. In these cases, the bandwidth-delay product is larger than the receiver advertised TCP congestion window size for connections with small congestion windows. As a result, the throughput is limited by the congestion window itself, not by the network bandwidth.

In Fig. 48, we plot the total TCP throughput. The proposed WFA scheme can maintain high channel utilization.

**h) Scenario 8 - Smaller AP Buffer Size:** We repeated the experiments of Scenario 3 when AP has a buffer size 20 packets. The wireless channel is errorless. The delayed TCP ACK mechanism is enabled. Fig. 49 - Fig. 52 present show the results. When the AP buffer is smaller, the WFA scheme results in 5% PER for nonsaturated UDP flows as can be seen from Fig. 49. Such losses are inevitable when the buffer size is too small. Still, the performance improvement in terms of fair access over the default DCF is very significant. As the other results imply, other performance improvements are independent of the AP buffer size and similar discussions hold.

VI. CONCLUSION

The work presented in this paper uses the idea of direction-based traffic differentiation in order to resolve the uplink/downlink unfair access problem in the 802.11e infrastructure BSS. We carried out a simulation-based analysis which showed that joint CW and TXOP differentiation is effective in fair and efficient channel access provisioning with marginal degradation on QoS support. This result is employed in a novel measurement-based dynamic EDCA parameter adaptation algorithm, namely WFA, that can provide a predetermined utilization ratio between uplink and downlink stations of the same AC while keeping the prioritization among ACs.

The proposed WFA scheme is unique in the sense that its design considers i) different transport layer protocol characteristics (for UDP and TCP), ii) the coexistence of stations with different bandwidth requirements (additional rate allocation block for UDP), iii) varying network conditions over time (parameter adaptation). Although WFA is directly applicable for TCP, we showed that there is a simpler extension of WFA, namely EPDA. The EPDA scheme implicitly makes use of the TCP being bi-directional and the 802.11e MAC being fair in the uplink in order to resolve the unfair access problem.
Through extensive simulations, we showed that the proposed framework provides short- and long-term station-based weighted fair access and efficient channel utilization for a wide range of scenarios. The QoS support for coexisting realtime connections is maintained at the same level (as of default EDCA). The proposed framework is standard-compliant.

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Fig. 1. Individual throughput of 12 uplink UDP (UDP$_{up}$), 12 downlink UDP (UDP$_{down}$), or 12 uplink TCP (TCP$_{up}$) and 12 downlink TCP (TCP$_{down}$) when the default EDCA or the proposed WFA scheme is employed at the AP (Scenario 1 in Section V).
Fig. 2. Fairness index $f$ for UDP data traffic when there are 5 uplink and 5 downlink realtime flows using 11 Mbps 802.11b PHY (Scenario 5 in Section V).
Fig. 3. Total throughput of all UDP flows using 11 Mbps 802.11b PHY (Scenario 5 in Section V).
Fig. 4. Average delay for realtime flows when there is UDP data traffic using 11 Mbps 802.11b PHY (Scenario 5 in Section V).
Fig. 5. Average jitter for realtime flows when there is UDP data traffic using 11 Mbps 802.11b PHY (Scenario 5 in Section V).
Fig. 6. Fairness index $f$ for TCP data traffic when there are 5 uplink and 5 downlink realtime flows using 11 Mbps 802.11b PHY (Scenario 5 in Section V).
Fig. 7. Total throughput of all TCP flows when there are 5 uplink and 5 downlink realtime flows using 11 Mbps 802.11b PHY (Scenario 5 in Section V).
Fig. 8. Average delay for realtime flows when there is TCP data traffic using 11 Mbps 802.11b PHY (Scenario 5 in Section V).
Fig. 9. Average jitter for realtime flows when there is TCP data traffic using 11 Mbps 802.11b PHY (Scenario 5 in Section V).
Fig. 10. Fairness index $f$ for UDP data traffic when there are 5 uplink and 5 downlink realtime flows using 54 Mbps 802.11g PHY (Scenario 5 in Section V).
Fig. 11. Total throughput of all UDP flows using 54 Mbps 802.11g PHY (Scenario 5 in Section V).
Fig. 12. Average delay for realtime flows when there is UDP data traffic using 54 Mbps 802.11g PHY (Scenario 5 in Section V).
Fig. 13. Average jitter for realtime flows when there is UDP data traffic using 54 Mbps 802.11g PHY (Scenario 5 in Section V).
Fig. 14. Fairness index $f$ for TCP data traffic when there are 5 uplink and 5 downlink realtime flows using 54 Mbps 802.11g PHY (Scenario 5 in Section V).
Fig. 15. Total throughput of all TCP flows when there are 5 uplink and 5 downlink realtime flows using 54 Mbps 802.11g PHY (Scenario 5 in Section V).
Fig. 16. Average delay for realtime flows when there is TCP data traffic using 54 Mbps 802.11g PHY (Scenario 5 in Section V).
Fig. 17. Average jitter for realtime flows when there is TCP data traffic using 54 Mbps 802.11g PHY (Scenario 5 in Section V).
Fig. 18. The instantaneous UDP throughput of individual uplink and downlink stations for WFA (Scenario 2 in Section V).
Fig. 19. The instantaneous TCP throughput of individual uplink and downlink stations for WFA (Scenario 2 in Section V).
Fig. 20. The instantaneous TCP throughput of individual uplink and downlink stations for EPDA (Scenario 2 in Section V).
Fig. 21. The instantaneous TCP throughput of individual uplink and downlink stations for WFA when delayed ACK is enabled (Scenario 2 in Section V).
Fig. 22. The instantaneous TCP throughput of individual uplink and downlink stations for EPDA when delayed ACK is enabled (Scenario 2 in Section V).
Fig. 23. $CW_{\text{min}}$ and TXOP adaptations at the AP and the stations for WFA when best effort flows use UDP (Scenario 2 in Section V).
Fig. 24. $CW_{\text{min}}$ and TXOP adaptations at the AP and the stations for WFA when best effort flows use TCP (Scenario 2 in Section V).
Fig. 25. $CW_{\text{min}}$ and TXOP adaptations at the AP and the stations for EPDA when best effort flows use TCP (Scenario 2 in Section V).
Fig. 26. $CW_{\text{min}}$ and TXOP adaptations at the AP and the stations for WFA when best effort flows use TCP with delayed ACK (Scenario 2 in Section V).
Fig. 27. $C_{\text{min}}$ and TXOP adaptations at the AP and the stations for EPDA when best effort flows use TCP with delayed ACK (Scenario 2 in Section V).
Fig. 28. Fairness index $f$ for saturated and Packet Loss Rate (PLR) for nonsaturated UDP stations when the default EDCA or WFA is employed with 0% PER at the wireless channel (Scenario 3 in Section V).
Fig. 29. Total UDP throughput when the default EDCA or WFA is employed with 0% PER at the wireless channel (Scenario 3 in Section V).
Fig. 30. Fairness index $f$ for saturated and Packet Loss Rate (PLR) for nonsaturated TCP stations when the default EDCA, WFA, or EPDA is employed with 0% PER at the wireless channel (Scenario 3 in Section V).
Fig. 31. Total TCP throughput when the default EDCA, WFA, or EPDA is employed with 0% PER at the wireless channel (Scenario 3 in Section V).
Fig. 32. Fairness index $f$ for saturated and Packet Loss Rate (PLR) for nonsaturated UDP stations when the default EDCA or WFA is employed with 0.1% PER at the wireless channel (Scenario 3 in Section V).
Fig. 33. Total UDP throughput when the default EDCA or WFA is employed with 0.1% PER at the wireless channel (Scenario 3 in Section V).
Fig. 34. Fairness index $f$ for saturated and Packet Loss Rate (PLR) for nonsaturated TCP stations when the default EDCA, WFA, or EPDA is employed with 0.1% PER at the wireless channel (Scenario 3 in Section V).
Fig. 35. Total TCP throughput when the default EDCA, WFA, or EPDA is employed with 0.1% PER at the wireless channel (Scenario 3 in Section V).
Fig. 36. Fairness index $f$ for saturated and Packet Loss Rate (PLR) for nonsaturated UDP stations when the default EDCA or WFA is employed with 1% PER at the wireless channel (Scenario 3 in Section V).
Fig. 37. Total UDP throughput when the default EDCA or WFA is employed with 1% PER at the wireless channel (Scenario 3 in Section V).
Fig. 38. Fairness index $f$ for saturated and Packet Loss Rate (PLR) for nonsaturated TCP stations when the default EDCA, WFA, or EPDA is employed with 1% PER at the wireless channel (Scenario 3 in Section V).
Fig. 39. Total TCP throughput when the default EDCA, WFA, or EPDA is employed with 1% PER at the wireless channel (Scenario 3 in Section V).
Fig. 40. Fairness index $f$ for saturated and Packet Loss Rate (PLR) for nonsaturated TCP stations when the default EDCA, WFA, or EPDA is employed with 0% PER at the wireless channel and delayed ACK mechanism is disabled (Scenario 3 in Section V).
Fig. 41. Total TCP throughput when the default EDCA, WFA, or EPDA is employed with 0% PER at the wireless channel and delayed ACK mechanism is disabled (Scenario 3 in Section V).
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Fig. 43. Fairness index $f$ for stations with 1, 2 or 3 UDP flows when the default EDCA, or WFA is employed (Scenario 6 in Section V).
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Fig. 45. Total throughput of UDP flows when the default EDCA, or WFA is employed (Scenario 6 in Section V).
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Fig. 47. Fairness index among all TCP flows with different congestion window sizes (Scenario 7 in Section V).
Fig. 48. Throughput of TCP connections when they use different congestion window sizes (Scenario 7 in Section V).
Fig. 49. Fairness index among all UDP when the AP buffer size is 20 (Scenario 8 in Section V).
Fig. 50. Throughput of UDP connections when the AP buffer size is 20 (Scenario 8 in Section V).
Fig. 51. Fairness index among all TCP flows when the AP buffer size is 20 (Scenario 8 in Section V).
Fig. 52. Throughput of TCP connections when the AP buffer size is 20 (Scenario 8 in Section V).