APPENDIX IV
FAIRNESS CONCEPT

The fairness concept is related to the probability that each node can be selected. Therefore, based on [8], we have

$$\phi_{R_I} = \frac{\beta_{S,R_{-I}}}{\beta_{S,R_I} + \beta_{S,R_{-I}}}$$
$$\phi_{D_J} = \sum_{I=1}^{2} \phi_{R_I} \frac{\beta_{R_I,D_{-J}}}{\beta_{R_I,D_J} + \beta_{R_I,D_{-J}}} \quad (19)$$

where ϕ_{R_I} is the probability that the router R_I can be selected as an intermediate router, and ϕ_{D_J} is the probability that the destination D_J can be the final destination. We note that for the normalized approach, $\beta_{i,j} = 1/2 \, \forall \, i, j$.

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A Novel Method of Serving Multimedia and Background Traffic in Wireless LANs

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***Abstract*—Wireless local area networks (LANs) require the efficient integration of multimedia and traditional data traffic. This paper proposes the Priority-Oriented Adaptive Polling (POAP) protocol that could be used in place of the enhanced distributed channel access (EDCA) part of the IEEE 802.11e access scheme. EDCA seems capable of differentiating traffic; however, it exhibits great overhead that limits the available bandwidth and degrades performance. POAP is collision free, prioritizes the different kinds of traffic, and is able to provide quality of service (QoS) for all types of multimedia network applications while efficiently supporting background data traffic. POAP, compared to EDCA, provides higher channel utilization, distributes resources to the stations adapting to their real needs, and generally exhibits superior performance.**

***Index Terms*—Adaptive polling, medium access control (MAC), quality of service (QoS), wireless local area network (LAN).**

I. INTRODUCTION

Nowadays, voice, audio, and video have to be efficiently transmitted along with the traditional data traffic. Real-time applications require QoS because they are time bounded, while slightly unreliable connections are allowed. On the other hand, data traffic does not demand particularly low delay, but reliability is essential. Thus, modern networks should be able to meet all types of traffic requirements. The IEEE 802.11e [1] workgroup has enhanced the Distributed Coordination Function (DCF) with QoS support, proposing enhanced distributed channel access (EDCA), which is the essential part of the 802.11e

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medium access control (MAC) protocol. However, it causes high overhead, which degrades the network performance; thus, efficiently serving multiple sources of different types of traffic is a challenge.

There are various MAC protocols proposed for different kinds of network conditions [2]–[8]. This paper proposes the Priority-Oriented Adaptive Polling (POAP) that is able to be built into IEEE 802.11e. It belongs to the centralized access protocols; however, no bandwidth reservation is required. It efficiently supports simultaneous real-time and background traffic by taking into account traffic priorities and the current status of the stations. It should be mentioned that despite the fact that EDCA is a distributed scheme, most network scenarios that consider real-time traffic assume an infrastructure topology with the use of an Access Point (AP) for packet relay and interconnection to the backbone network. POAP tries to exploit this common topology by using the AP for access control. Notice that 802.11e also proposes a polling protocol called Hybrid Control Channel Access (HCCA) [1]; however, it does not adopt packet priorities and reserves resources to exclusively serve real-time traffic. It is a specialized protocol that cannot operate independently. Thus, POAP is only compared with EDCA since they have the same role. This paper assumes that stations can directly communicate when in range; however, AP could be also used as a packet forwarder. 802.11e also provides a Direct Link Protocol.

This paper is organized as follows. Section II presents the 802.11e MAC. In Section III, POAP is analyzed, focusing on the polling scheme, the priority model, and the station choice algorithm. Section IV presents our simulator, the network scenario, and the results, which prove the efficiency of POAP by comparing it with EDCA. Section V concludes this paper.

II. IEEE 802.11e MAC

The legacy IEEE 802.11 MAC does not support QoS. However, some modifications that enhance partial QoS support have been proposed [8]. The need for QoS has led to IEEE 802.11e. The provided MAC mechanism is the Hybrid Coordination Function (HCF). The latter consists of two parts: EDCA, which is the mandatory access scheme for 802.11e and is contention based, and HCCA, which is centralized and based on resource reservation.

EDCA is the QoS-enhanced version of the DCF employed by the legacy 802.11 MAC. When a station needs to transmit and the channel is busy, it waits until the medium becomes idle and then defers for an extra interval, i.e., Arbitrary Distributed Interframe Space (AIFS). If the channel stays idle for the AIFS interval, the station then starts backoff by selecting a random number of slots from a contention window (CW). The backoff counter is decreased only when the channel is sensed idle. When it reaches zero, the packet is transmitted, and the station waits for an acknowledgement (ACK). If the ACK is not received within a specific period, the station will invoke a backoff and retransmission procedure using a larger window. An additional Request To Send/Clear To Send (RTS/CTS) handshake scheme is defined to deal with hidden stations.

In EDCA, the QoS support is realized with the introduction of access categories (ACs). The packets are delivered through multiple backoff instances within one station, with each backoff instance parameterized with AC-specific parameters. In every station, there are four packet buffers corresponding to the four ACs. The eight possible user priorities assigned to the generated traffic are mapped to the four ACs. This makes traffic differentiation possible. Each AC within the stations independently contends for access and starts backoff after detecting the channel idle for an AIFS. To favor higher priority traffic, higher ACs are assigned lower AIFS values. Furthermore, the higher the AC, the smaller its CW will be. Thus, a high-priority packet will probably choose a smaller backoff, increasing its chances to "win" the channel contention.

This model provides only minimal QoS. The backoff procedure leads to a waste of bandwidth, and the hidden stations cause collisions despite the backoff mechanism. The RTS/CTS handshake limits this problem; however, it increases the overhead. Some approaches that enhance EDCA can be found in [9]–[11]. An analysis on the performance limits caused by EDCA overhead can be found in [12]. EDCA definitely enhances DCF with QoS; however, it is shown that it can actually serve only limited traffic of low QoS demands. Thus, we propose POAP, which greatly reduces overhead and optimizes the priority model, providing stricter QoS and higher performance.

When HCCA is also implemented in HCF, the 802.11e superframe is divided into HCCA and EDCA periods. The stations that want to transmit real-time data with guaranteed QoS ask the Hybrid Coordinator (HC) for resource reservation. The HC schedules transmissions during the HCCA periods and accordingly grants the stations with channel access. HCCA is a complementary protocol in the HCF scheme. It is not a standalone access method, and according to the 802.11e standard, it is only supposed to operate combined with EDCA. Thus, the direct comparison of HCCA with POAP has no meaning and is actually not feasible. POAP and HCCA are different kinds of protocols. POAP tries to effectively serve mixed-type traffic, whereas HCCA cannot even participate in such a simulation scenario, since it can only handle real-time traffic. For these reasons, HCCA is not taken into account when evaluating the POAP protocol.

III. POAP Protocol

According to POAP, the AP polls the stations to give them permission to transmit. The polling scheme eliminates collisions and causes low overhead. A single channel is adopted, the Tx–Rx data rates are assumed to be identical, and channel access is based on a time-division multiple-access scheme described below. The protocol uses the POLL, NO_DATA, and STATUS control packets with transmission duration t_{POLL}, t_{NO_DATA}, and t_{STATUS}, respectively. A STATUS packet is marked as ACK or NACK according to the specific case. The transmission duration of a DATA packet is t_{DATA}, and the propagation delay is t_{PROP_DELAY}. The possible polling events are as follows.

1) The AP polls an inactive station. The AP sends POLL to the station at time t. The station responds with a NO_DATA packet, which is received by the AP at $t + t_{POLL} + t_{NO\_DATA} + 2t_{PROP\_DELAY}$. Then, a new poll is initiated.
2) The AP polls an active station. The AP sends POLL to the station at time t. The station replies with a STATUS packet marked as ACK, which carries the destination address and the size of the following DATA packet. Then, the polled station starts transmitting the DATA packet directly to the destination. Upon reception, the destination broadcasts a STATUS packet marked as ACK. Otherwise, if the reception fails but the station had successfully identified the source's STATUS packet whereby it realized that the following DATA packet was destined to it, it responds with a STATUS packet marked as NACK. The transmission of a NACK is not wasted time since either way, the stations had to wait for a possible ACK. A new poll is initiated at $t + t_{POLL} + t_{DATA} + 2t_{STATUS} + 4t_{PROP\_DELAY}$. We consider a variable DATA packet size; thus, t_{DATA} is not static. Specifically, t_{DATA} depends on the size of the currently transmitted packet.
3) The communication fails. In the case in which the station does not receive the POLL packet, the polling fails. The AP has to wait for the maximum polling cycle before proceeding to a new poll, since it has to be certain that it will not

collide with a possible transmission. When the POLL packet is received by the polled station, but then the AP fails to receive any feedback, it waits for the maximum polling cycle similar to the previous case. The duration of the maximum polling cycle is $t_{POLL} + t_{MAX\_DATA} + 2t_{STATUS} + 4t_{PROP\_DELAY}$, where t_{MAX_DATA} is the duration of the largest allowed DATA packet. At the end of this cycle, it is certain that the medium is idle. When such a communication failure occurs, the AP lowers the probability to choose this station in the new polling procedure assuming a bad link between them. However, it is most likely that the AP will receive some feedback either from the polled or from the destination station.

This scheme provides an efficient feedback and low overhead. The purpose of the control packets is to keep the concerned stations informed of the network status and minimize the idle intervals. The AP needs to monitor the transmissions so that it can proceed to the next poll right after the completion of a communication. Thus, it has to be aware of the actual duration of the polling cycle. To gain this knowledge, the AP just has to detect the NO_DATA packet or the STATUS ACK packet, which contains the duration of the following data transmission, or the DATA packet from the polled station or the STATUS ACK–NACK packet from the destination station. Indeed, when POLL is successfully received, then it is most likely that the AP will obtain the necessary feedback. Moreover, it should be mentioned that despite the fact that each station is supposed to send a single DATA packet per transmission, it is possible to have multiple successive data packets destined to the same station with total duration no longer than t_{MAX_DATA} and a single block acknowledgement for all these packets. This way, bursty traffic with strict requirements could be more effectively supported.

The POAP packet choice mechanism first considers the priority (AC) of each buffer so that high-priority traffic is favored. In addition, to provide low packet delays, low packet drops, and fairness among the ACs, the number of packets in each buffer is taken into account. Specifically, heavy loaded buffers should have higher probabilities of transmitting. Finally, the earlier generated packets are favored.

A polled station initially examines if it has any buffered packets; otherwise, it replies with NO_DATA. Then, each buffer is examined to calculate its normalized priority P_{PR} and normalized number of buffered packets P_B. Assuming that the priority of buffer i is $p[i] = i + 1$, so that it is not null for $AC[0]$, then it holds that $P_{PR}[i] = p[i]/\sum_{k=0}^{3} p[k]$. In addition, if $b[i]$ is the number of packets carried by buffer i, then it holds $P_B[i] = b[i]/\sum_{k=0}^{3} b[k]$. The buffer priority and the number of buffered packets should have different contributions to the final buffer choice probability P. Thus, we use the weights W_{PR} (default value 6) and W_B (default value 2) for P_{PR} and P_B, respectively. Obviously, when, in the network configuration, the purpose is to extendedly favor high-priority traffic, then W_{PR} is set to a high value compared to W_B; otherwise, if the configuration should be able to efficiently serve highly loaded stations, then the value of W_B is raised. The default values have resulted from the actual meaning of the parameters and tests, which have shown that when the priority weight is three times higher than the buffer load weight, then the buffer choice probability ensures the combination of efficient traffic differentiation and relatively low packet delays for all buffers in most network conditions. We use the values 6 and 2 rather than 3 and 1, because value 1 is assigned to the weight W_T, which is introduced later. The nonnormalized choice probability for buffer i is $P[i] = W_{PR} \times P_{PR}[i] + W_B \times P_B[i]$. As mentioned above, when W_{PR} is high compared to W_B, it is most probable that a high-priority buffer will be chosen for transmission. On the other hand, if W_B is increased, it is more probable to choose a packet from a highly loaded buffer. The normalized choice probability is equal to $P[i]/\sum_{k=0}^{3} P[k]$. After the buffer selection, the station chooses to send the earliest generated packet in it.

Before the AP decides which station to poll, it has to be well informed of their buffers' status. Thus, we exploit the ACK and NACK messages, which are already useful. Specifically, the STATUS packet, apart from acknowledging receptions, also carries its source's priority score, which is an indication of the status of the station's buffered traffic. The priority score depends on the priority and the load of each buffer. For station j, the priority score is $P_S[j] = \sum_{k=0}^{3} p[k] \times b[k]$. So, the AP examines every broadcasted STATUS packet to update the stored priority scores. This way, the model provides efficient feedback with minimum overhead. At this point, it should be mentioned that the AP lowers the probability of polling a station after a communication failure by halving its stored priority score.

The first factor considered by the algorithm that chooses the polled station is the priority score. The second factor is the time elapsed since the last poll of each station (τ). Specifically, to provide fairness and avoid the total exclusion of stations that are inactive for quite some time, the stations that have not been polled for a long time are favored to some degree. The AP, which also participates in the contention, is assigned a higher access probability because of its central role.

Here, we present the operation of the algorithm that returns the station to be polled. Initially, we check if the AP has any buffered packets. If it has not, then it is not included in this procedure. Then, the priority score of each considered station j is normalized as $P_P[j] = P_S[j]/\sum_{l=0}^{M-1} P_S[l]$, where M is the number of stations considered by the algorithm. The time elapsed since its last polling is also normalized as $P_T[j] = \tau[j]/\sum_{l=0}^{M-1} \tau[l]$. The nonnormalized final probability of polling station j is $P_{POLL}[j] = W_{PR} \times P_P[j] + W_T \times P_T[j]$, where W_T (default 1) is the weight of the contribution of the P_T factor. Obviously, a station that has not been polled for a long time has a high P_T value, so its polling probability increases. A high W_T value provides extended fairness among stations; however, this way, traffic differentiation fades. If the examined station j is the AP, then its nonnormalized final access probability is multiplied by the factor W_{AP} (default 10) so that it has clearly higher access chances. Lastly, the AP chooses a station to be polled according to each one's normalized polling probability, which, for station j, is $P_{POLL}[j]/\sum_{l=0}^{M-1} P_{POLL}[l]$.

Regarding the overhead caused by POAP, it would be interesting to have a quantitative comparison with EDCA. Thus, we calculate the duration of a communication without counting the data packet transmission time by considering the default parameter values for EDCA (AIFS duration, CW duration, RTS size, CTS size, and ACK size), assuming that this is the first transmission attempt and that the data rate is 36 Mb/s. Concerning POAP, the POLL packet size is 80 bits plus the physical header, and the STATUS packet size is 160 bits plus the physical header. In such a case, the time interval while no real data are transmitted during an EDCA communication is on average equal to 168 μs for the lowest priority traffic and 69 μs for the highest priority traffic, whereas for POAP, it is 27.5 μs. Obviously, POAP causes a significantly lower overhead than EDCA, even when no collisions and retransmission attempts are considered for the EDCA scheme.

IV. Simulation Results

We developed a C++ simulator that employs the IEEE 802.11g physical layer and the 802.11e superframe. The condition of any link was modeled using a three-state machine (Good, Bad, and Hidden). The propagation delay is assumed to be 0.5 μs, which corresponds to 150-m distances. We consider one bidirectional voice–video communication between the AP and each mobile station. In addition, there is a bidirectional Transmission Control Protocol (TCP) flow

TABLE I
CHARACTERISTICS OF THE TRAFFIC TYPES USED IN THE SIMULATION SCENARIO

Traffic Type	Coding	Packet Data Size (bytes)	Packet Inter-arrival Time (ms)	On/Off Periods (sec)	Data Bit Rate	Packet Delay Bound (ms)	User Priority
TCP Flow	-	1500	Expo. 10 (mean)	Always On	~1200 Kbps (VBR)	60000	1
Voice	G.726 (ADPCM)	80	20	Expo. (mean) On: 1.5 Off: 1.8	32 Kbps (CBR)	75	6
Live Video	H.264 [CIF-20fps]	750	10	Always On	600 Kbps (CBR)	200	5

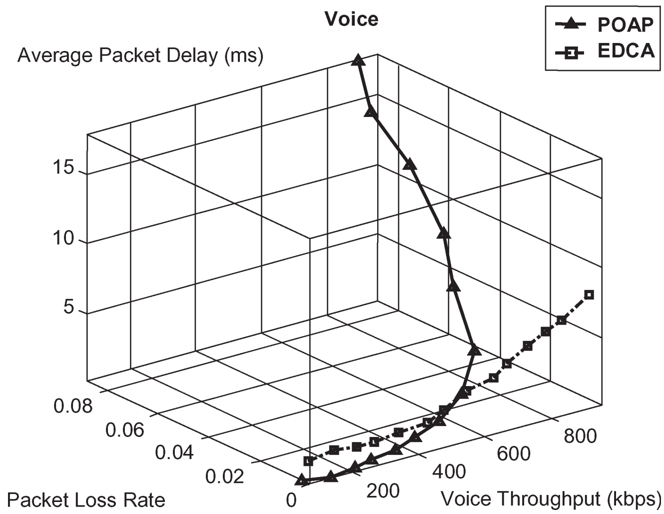

Fig. 1. Voice. Average packet delay and loss rate versus voice throughput.

between any two adjacent mobile stations. The traffic has realistic characteristics derived by the analysis of traces. We use TCP flows with features typical for file transfers. Voice communication is based on the G.726 codec. The new H.264 codec is employed for live video. Specifically, the characteristics of the considered traffic are presented in Table I. We simulated 14 wireless LAN topologies, starting with two mobile stations, finally reaching 28 mobile stations with a step of 2. Regarding the EDCA configuration, the default parameters' values for all ACs were used. Neither tuned configuration for real-time nor background traffic was adopted because the simulation scenario involves the integration of different types of traffic. Our objective was to evaluate the capability of POAP and EDCA in simultaneously handling voice, video, and background traffic.

Regarding voice, in Fig. 1, it can be seen that POAP exhibits lower packet delays and loss rates when the voice throughput is lower than 550 kb/s, whereas EDCA performs better for higher values. However, both protocols achieve a similar maximum throughput. Despite the fact that POAP eventually causes higher packet delays, it keeps them below 18 ms, which is very satisfactory for voice communications. The conclusion is that both schemes are able to provide QoS in voice transmissions. The above behavior is due to the fact that POAP conserves resources to serve video and TCP traffic as well, whereas EDCA favors the voice packets to such a degree that seems unable to simultaneously serve video and TCP flows.

Fig. 2 shows that EDCA suffers from so many packet losses that it cannot support live video when its throughput is over 3 Mb/s. POAP

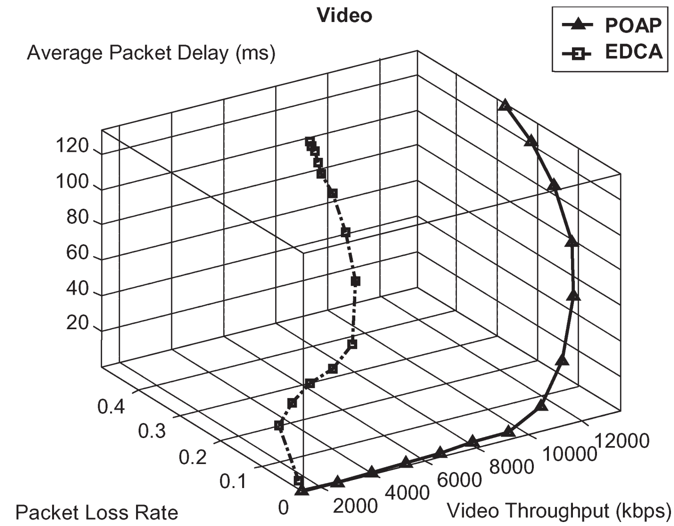

Fig. 2. Video. Average packet delay and loss rate versus video throughput.

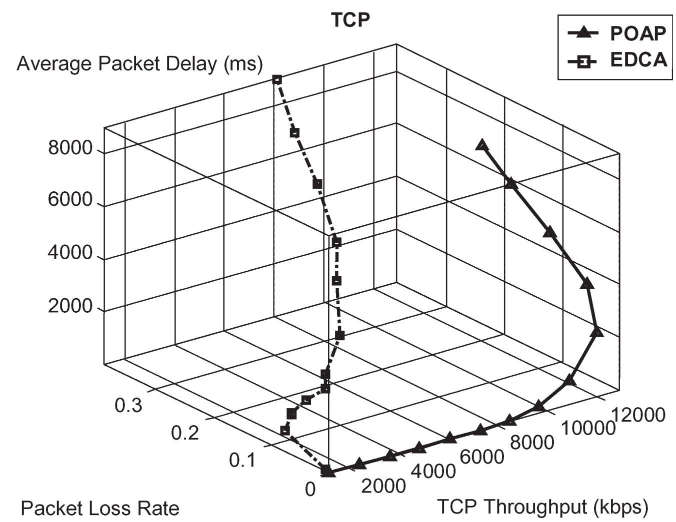

Fig. 3. TCP. Average packet delay and loss rate versus TCP throughput.

exhibits particularly low packet delays and loss rates when the video throughput is lower than 12 Mb/s while it achieves a notably high throughput.

According to Fig. 3, POAP can efficiently support background traffic at the same time that it provides QoS for voice and video. It guarantees significantly lower packet delays and loss rates while it achieves higher throughput than EDCA.

In our effort to examine the overall network performance for both protocols, we have plotted in the same 3-D graph the average bit delay and the bit loss rate versus the total throughput for the whole offered traffic. In Fig. 4, it can be seen that POAP exhibits quite steady performance while achieving clearly higher total throughput and lower loss rate than EDCA.

Notice that the packet loss rate results from the number of packet drops occurring due to the expiration of the packet lifetime or buffer overflow. Since the adopted buffer size is 1 MB, the overwhelming majority of voice and video packet drops are caused by the expiration of their lifetime, whereas the TCP packet drops are due to buffer overflow. Obviously, as the offered traffic load increases, it becomes particularly difficult to perfectly serve all flows. Generally, POAP exhibits higher channel utilization than EDCA. The latter favors voice traffic to such an extent that it is not capable of simultaneously supporting video and

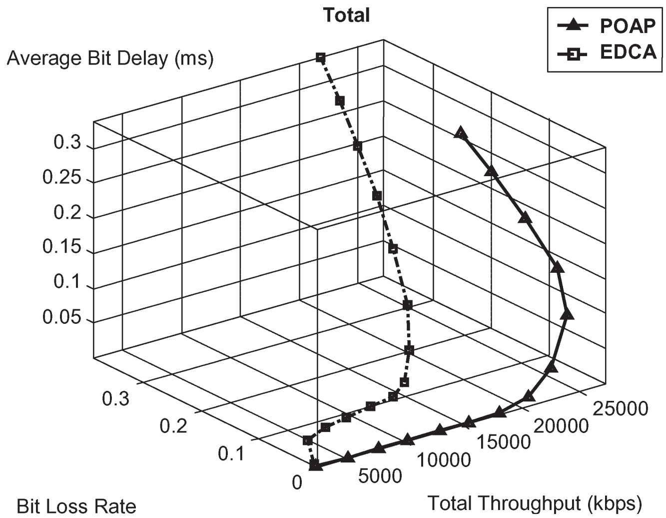

Fig. 4. Total traffic. Average bit delay and loss rate versus total throughput.

TCP traffic. In POAP, the polling scheme provides minimum overhead with optimized feedback and zero collisions. Since the AP is aware of the traffic status, it accordingly adapts the resources granted to the stations. Furthermore, POAP ensures that no flow or station can dominate the medium.

V. Conclusion

The proposed POAP protocol can be adapted into the IEEE 802.11e MAC in place of EDCA. It employs station polling, resulting in zero collisions. Notice that despite the distributed nature of EDCA, its most common topology when serving integrated data is also an infrastructure one. POAP efficiently provides QoS to integrated time-bounded and background traffic. Traffic differentiation is based on packet priorities. To provide the AP with valuable feedback, POAP efficiently exploits the use of control packets. This information allows the AP to optimize its decisions about the access grants. It is shown that POAP exhibits higher channel utilization since it eliminates the overhead caused by contention and collisions. Furthermore, it provides significantly lower packet delays, lower loss rates, and higher throughput. As future work, the network parameters could be further tuned. In addition, POAP could be combined with a resource reservation scheme to provide guaranteed QoS.

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Rate Maximization for Downlink OFDMA With Proportional Fairness

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***Abstract*—In this paper, we study the sum throughput maximization with access proportional fairness (APF) for downlink orthogonal frequency-division multiple access (OFDMA) channels. We propose selective multiuser diversity (SMuD) schemes with normalized signal-to-noise ratio (n-SNR)-based ranking for user selection at each carrier to achieve long-term fairness. We also propose a modified absolute signal-to-noise ratio (a-SNR)-ranking-based SMuD scheme, which provides improved performance over the original a-SNR SMuD scheme. The total transmit power is assigned to the allocated carriers using either equal power allocation (EPA) or water filling. Closed-form throughput and fairness expressions for both the n-SNR and a-SNR SMuD schemes with EPA over Rayleigh channels are derived, which are accurate for even highly correlated frequency channels. Numerical results show that the long-term fairness gives a substantially higher rate than the more stringent short-term fairness. The n-SNR scheme brings perfect access fairness; the sum rate is slightly degraded compared to the a-SNR scheme without fairness, and it is not very sensitive to the imperfect estimation of the average channel signal-to-noise ratio. These results put new insight into the achievable downlink OFDMA performance with proportional fairness and the effects of various system and channel parameters.**

***Index Terms*—Multiuser diversity, orthogonal frequency-division multiple access (OFDMA), proportional fairness, throughput maximization, water-filling (WF) power allocation.**

I. Introduction

Orthogonal frequency-division multiple access (OFDMA) is a promising candidate modulation-and-access scheme for fourth-generation communication systems [1]–[6]. The capacity maximization under the transmit power and fairness constraints has been a research focus for OFDMA systems [1], [2], [4], [5], [7]–[12]. In OFDMA, K users share N carriers, and multiuser diversity can be exploited to improve the throughput and provide a scheduling gain

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