Achieving Temporal Fairness in Multi-Rate 802.11 WLANs with Capture Effect

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Abstract— **This paper proposes new MAC layer transmission opportunity (TXOP) adaptation algorithms for achieving temporal fairness in multi-rate 802.11 WLANs, which take underlying capture effect into account. Due to capture effect, a frame with the strongest received signal strength can be correctly decoded at the receiver even in the presence of transmission collisions from multiple contending stations. This effect introduces significant imbalance in channel access probabilities, and consequently the use of equal TXOP for each contending station cannot achieve temporal fairness. We develop a centralized and a distributed TXOP adaptation algorithm that compensate the stations with less channel access opportunities by giving them larger TXOPs. In the proposed centralized scheme, the access point estimates the successful TXOP acquisition probability of each associated station and allocates appropriate TXOPs to the contending stations. In the proposed distributed algorithm, each station estimates its own share of channel occupation time and adjusts its TXOP individually. We present the conditions that ensure the convergence of the distributed algorithm. Simulation results show that our proposed schemes can effectively achieve "true" temporal fairness.**

I. Introduction

IEEE 802.11 [1] is the *de facto* standard for Wireless Local Area Networks (WLANs). Its fundamental medium access mechanism is the Distributed Coordination Function (DCF). In the long term, the DCF provides equal transmission opportunities to the competing STAs when they experience similar channel conditions. If the STAs also transmit the frames of the same size, this equal channel access opportunity results in an equal share of bandwidth or throughput. In this context, the 802.11 DCF is known to provide a "throughput-fair" channel access.

Today's 802.11 WLANs provide multiple data transmission rates by employing different sets of modulation and channel coding schemes. Since the DCF provides throughput-based fairness, the performance of the high-rate STAs is bounded by the performance of the STAs using lower rates. This phenomenon is referred to as a performance anomaly of the 802.11 [3]. Hence, it is more appropriate to provide temporal fairness, i.e., each contending STA receives an equal share of channel occupation time. It has been shown that this notion of fairness can achieve significant improvement in aggregate throughput while guaranteeing that no STA receives worse channel access than it would in a single rate WLAN [4,5]. IEEE 802.11e [6] extends the 802.11 with QoS capability to support real-time applications. The Enhanced Distributed Channel Access (EDCA) is the mandatory channel access function of 802.11e and extended from DCF. IEEE 802.11e introduces the concept of transmission opportunity (TXOP), which represents a STA's channel holding time. Once a STA wins the channel contention, it can hold the channel for the duration of a TXOP, in which one or more frames can be transmitted in a burst, separated by SIFS and free of contentions.

Prior work [7] suggests allocating the same value of TXOP to the contending STAs for achieving temporal fairness. It implicitly requires two assumptions for this approach to be effective. First, the contending STAs have equal channel access probabilities. Second, when collisions occur all the involved frames are corrupted regardless of their signal strength. However, in reality collisions are often resolved in the way that the frame with stronger signal strength is successfully received provided it is stronger enough compared to other colliding frames. This is referred to as physical layer capture (PLC) effect [8]. PLC violates the above two assumptions. First, when other stations involved in a collision see their frames corrupted and refrain their subsequent transmissions, the STA with stronger signal (capturing station) successfully obtains a transmission opportunity. Second, the binary exponential backoff (BEB) of the DCF (EDCA) favors last succeeding STA by resetting its contention window (CW) to CW_{min}, while doubling the CWs of other involved STAs. In the long term, the capturing STA achieves higher channel access probability because of a smaller average CW. To the best of our knowledge, none of the previous studies [7,10,11,12,13] on MAC fairness have accurately considered the impact of physical layer capture effect.

In this paper, we consider a WLAN basic service set (BSS) that comprises an AP and a set of multi-rate STAs. The STAs tend to stay in the same physical locations for long time periods and thus generate long-lived traffic flows. We investigate the impact of capture effect on fairness, and explain why capture effect causes significant unfairness among contending stations. To achieve temporal fairness, we develop a centralized and a distributed TXOP adaptation algorithm that compensate for unbalanced channel access probabilities with different TXOP sizes. Throughout this paper we assume no packet losses due to channel errors. This assumption is backed up by rate adaptation function through which a STA reacts to noisy channel by reducing the data rate (i.e., using a more reliable modulation scheme to reduce the error rate). In other words, we assume that the STAs in our network have already adapted their date rates according to the channel conditions so that they can reliably transmit.

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The rest of the paper is organized as follows. Section II investigates the impact of capture effect on fairness. Section III proposes the centralized and distributed TXOP adaptation algorithms for achieving temporal fairness in the presence of capture effect. In Section IV, we evaluate the performance of the proposed algorithms. Finally, Section V concludes our work.

II. Capture Effect And Fairness

Due to capture effect, a frame with the strongest received signal strength can be correctly decoded at the receiver even in the presence of simultaneous transmissions of multiple stations.

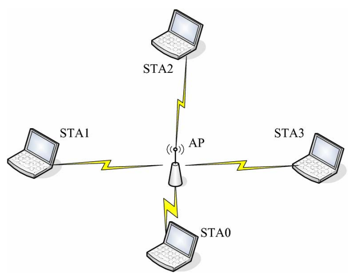


Figure 1. Network topology to illustrate unfairness caused by capture effect

To show how capture effect impacts fairness, we consider the network of Fig. 1, where the STAs are greedy users and always have frames to send. The original DCF is used as the underlying MAC layer protocol, so a TXOP here refers to the single-frame transmission time. STA 0 is the capturing STA and thus can always transmit its frames successfully even when collisions occur. STAs 1, 2 and 3, however, will experience transmission failures in the collisions. In our simulations, all the STAs have the same frame size of 1052 bytes, the same data rate of 2Mbps and the same transmit power. We measure the average throughput, channel access probability P_{ac}, conditional TXOP initiation success probability $P_{s|ac}$ and successful TXOP acquisition probability P_S of each STA.

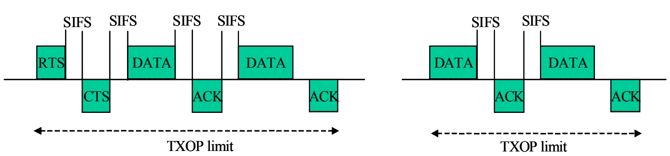


Figure 2. Illustration of frame burst in a TXOP: left – RTS/CTS/DATA/ACK mode; right – DATA/ACK mode

The *channel access probability* of a STA is defined as the probability that the STA attempts to access the wireless medium (or to initiate a TXOP) according to the DCF or EDCA channel access rules. As shown in Fig. 2, a STA starts a TXOP with an RTS-CTS or DATA-ACK frame exchange sequence. Only this first frame exchange participates in channel contention. Once the STA wins upon the successful completion of the first frame exchange, it holds the channel till the end of the TXOP and transmits all subsequent frames contention- and collision-free. In this way, the entire frame burst appears to be a single instance of the wireless channel activity to other STAs. The *conditional TXOP initiation success probability* of a STA is defined as the probability that a TXOP initiation attempt by a STA is successful, i.e. the probability that the first frame exchange in a TXOP initiation attempt is successful. The *successful TXOP acquisition probability* P_s of a STA is the multiplication of P_{ac} and $P_{s|ac}$. It is the probability that the STA successfully obtains a TXOP for frame transmissions.

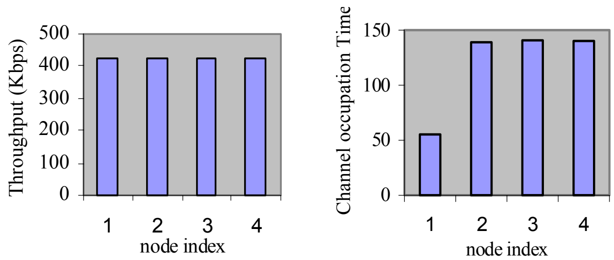
We provide the simulation results in Table I. The first row of the Table shows the average throughput of each STA. We see that STA 0 achieves as twice throughput as other STAs. Since we assume no channel errors and only consider frame losses due to collisions, it is physical layer capture that causes such imbalance in throughput. The measured P_{ac}, $P_{s|ac}$ and P_s of each STA are given in the last three rows of the Table. It can be seen that capture effect impacts the performance of the contending STAs in two folds. (1) When other STAs involved in a collision see their first frame exchange corrupted and refrain their access to the channel, the capturing STA successfully obtains a transmission opportunity. This implies a higher $P_{s|ac}$ for the capturing STA; (2) since the binary exponential backoff of DCF (EDCA) favors last succeeding STA, the capturing STA therefore achieves a higher channel access probability P_{ac} due to a smaller average CW. Due to the two effects, the capturing STA achieves higher throughput.

TABLE I
Average Throughput, Channel Access Probability And Conditional TXOP Initiation Success Probability

	STA 0	STA 1	STA 2	STA 3
Average throughput (Kbps)	629	327	331	316
Channel access probability	0.3310	0.2248	0.2268	0.2174
Conditional TXOP initiation success probability	1.0000	0.7661	0.7679	0.7642
Successful TXOP acquisition probability	0.3310	0.1722	0.1742	0.1661

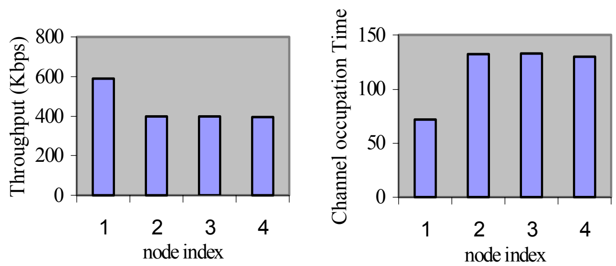
When contending STAs use different data transmission rates, a fast STA will pay a penalty for competing against slow STAs if throughput based fairness is considered. Since a STA with lower data rate will take longer time to transmit the same amount of data than the STA with higher data rate, the channel is being used most of the time by the slower STAs. To illustrate this, we first consider the network of Fig. 1 without capture effect (i.e., all the involved frames are corrupted in a collision). With multi-rate capability, STA 0 is able to use 11Mbps data rate, while other STAs still use 2Mbps. We measure the average throughput and channel occupation time for each STA and present the results in Fig. 3. The *channel occupation time* of a STA is defined as the time in which the STA successfully transmits frames on the channel. Since we do not consider capture here, each STA achieves equal successful TXOP acquisition probability (P_S) and thus equal throughput. However, channel occupation time of the fast STA (STA 0) is almost 1/3 of the channel occupation time of any other STA. In total, nearly 7/8 of the channel time is devoted to the 2Mbps STAs. Furthermore, despite that a STA has increased the data rate to 11Mbps, the total throughput (~1600Kbps) almost remains the same as above where all 4 STAs used 2Mbps.

Second, when capture effect is present, neither throughput-based nor temporal fairness can be achieved, as shown in Fig. 4. However, we observe an increase in the total throughput. This is because due to capture effect the high-rate STA (capturing STA) has more opportunities to transmit.



(a) Throughput (b) Channel occupation time

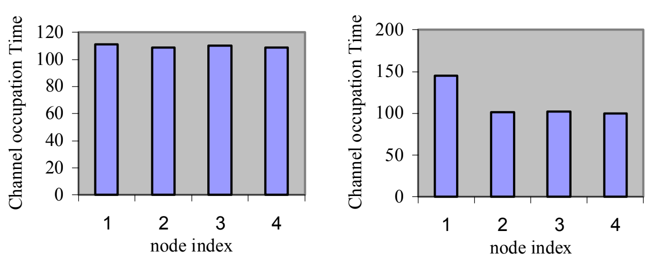
Figure 3. Throughput and channel occupation time in the absence of capture effect: throughput-based fairness can be achieved, but faster station (STA 0) obtains the least channel occupation time



(a) Throughput (b) Channel occupation time

Figure 4. Throughput and channel occupation time in the presence of capture effect: neither throughput-based fairness nor temporal fairness can be achieved

In view of these issues, it is more advantageous to use temporal fairness in multi-rate WLANs, in which each contending STA receives an equal share of channel occupation time. However the impact of physical layer capture needs to be factored in when temporal fairness schemes are designed.



(a) In the absence of capture (b) In the presence of capture

Figure 5. STAs' channel occupation time using the same TXOP: temporal fairness can be achieved in the absence of capture effect, but cannot be achieved in the presence of capture effect

Prior work [7] targets at temporal fairness but failed to consider the capture effect. It suggests allocating the same value of TXOP to the contending STAs. This approach, however, is not effective in the presence of capture. Fig. 5 compares channel occupation time of individual STAs using the same value of TXOP for each channel access, with and without capture. As above, STA 0 uses a data rate of 11Mbps, while others use 2Mbps. Since the capturing STA has more opportunities to successfully acquire TXOPs, it gets MORE THAN FAIR channel occupation time under the same TXOP policy. In the next section, we propose two TXOP adaptation algorithms for achieving temporal fairness, with the consideration of capture effect.

III. TXOP Adaptation Algorithms

A. Temporal Fairness

Let P_{si} denote STA i's probability of successful TXOP acquisition (as defined in Section II) and X_i be its TXOP. Temporal fairness implies

$$P_{si} X_i = P_{sj} X_j \qquad \forall i, j \tag{1}$$

Eq. (1) provides the basic idea of our temporal fairness algorithms, that is, using longer TXOP time to properly compensate for lower channel access probability of a STA.

Note that (1) only imposes a requirement on the ratios of X_i and X_j, not on their absolute values. We note that some choices of TXOPs will enforce fragmentation on every frame at some STAs (i.e., when the chosen X_i is shorter than the time needed to transmit one frame). To avoid excessive fragmentation overhead, we choose carefully the set of TXOPs satisfying (1) so that every STA can transmit at least one frame during its TXOP. Such choice is feasible, since the solution to (1) is not unique. Specifically, if $\{X_1, X_2, \ldots X_m\}$ qualifies, $\{CX_1, CX_2, \ldots CX_m\}$ also works, where C is any non-zero constant. We defer the discussion on the choice of TXOPs to the next subsections.

B. Centralized Temporal Fairness Algorithm

In the centralized algorithm, the AP is responsible for assigning appropriate TXOP limits to the contending STAs. Given P_{si}, frame size L_i and data rate R_i of a STA i, the AP allocates the TXOP limit for each STA as follows. Let T_{si} denote STA i's frame transmission time. In the DATA/ACK basic mode, $T_{si} = L_i / R_i + T_{sifs} + T_{ack}$, while in the RTS/CTS mode, $T_{si} = T_{rts} + T_{cts} + L_i / R_i + T_{ack} + 3T_{sifs}$, where T_{rts}, T_{cts} and T_{ack} represent the transmission times of RTS, CTS and ACK frames, respectively. T_{sifs} is the short inter frame space (SIFS). Considering that the RTS/CTS exchange only occurs at the beginning of a frame burst and that two consecutive frame transmissions in a TXOP are separated by SIFS, we let

$$T_{si} \approx \frac{L_i}{R_i} + T_{ack} + 2T_{sifs}$$

for both access modes in the following derivation. We denote with n_i the number of frames that STA i can transmit within the X_i duration, that is, $n_i = X_i / T_{si}$. Note that n_i could be a fractional number. Insert this relationship into (1), we get, for all i, j,

$$P_{si} n_i T_{si} = P_{sj} n_j T_{sj} \tag{2}$$

We then define

$$K_i = P_{si} T_{si} \text{ and } K_{\max} = \max_i \{K_i\}$$

To satisfy (2), the STA with $K_{\max}$ must have the smallest value of n, denoted by n_{min}. Then, for any STA i, we have,

$$K_i n_i = K_{\max} n_{\min}$$

We normalize n_{min} to 1 and get $n_i = n_{min} . K_{max} / K_i \geq 1$. The resulting TXOPs enable the STA with K_{max} to transmit exactly one frame, while others to transmit more than one frame in one TXOP. They constitute the smallest set of $\{X_i\}$, which satisfies (1) and ensures that any STA can transmit at least one frame in its assigned TXOP limit.

To avoid fragmentation at the end of a TXOP, a STA only transmits an integral number of frames within a TXOP. The residual TXOP time, $(n_i-[n_i])T_{si}$, of a STA is then released for other STAs' use, where $[n_i]$ is the largest integer not greater than n_i. In our algorithms, for a STA to fully exploit the granted channel time, we allow the STA to roll over its released (unused) TXOP time to its next TXOP. For example, if n_i is calculated as 2.5, STA i only transmits two frames during the current TXOP. The residual time ($0.5T_{si}$) is then released and accumulated to STA i's next TXOP. STA i's next transmission time then becomes $X_i + 0.5T_{si}$, during which it can transmit 3 frames assuming no other change in the TXOP allocation. Note that this policy is different from that specified in the IEEE 802.11e. In 802.11e, this portion of time represents a waste for the STA that releases the channel.

To implement the centralized algorithm, the AP measures each STA's probability of successful TXOP acquisition by counting received frame bursts from each source STA. Let N_i denote the number of TXOPs successfully acquired by STA i out of the total N TXOPs successfully acquired by all the contending STAs. When N is large enough, N_i/N is a good estimate for the TXOP acquisition probability P_{si} of STA i. After the AP receives a measurement window (MW) of N frame bursts, i.e., N successful TXOPs acquired by all the STAs, it updates the probability estimates, calculates the appropriate TXOP limits for STAs and broadcasts the TXOP assignments in its beacon frames. The AP counts frame bursts instead of individual frames because a frame burst (back-to-back frames transmitted within a TXOP) appears to be a single instance of the wireless channel activity, in which only the first frame exchange in the burst contends for the channel while all subsequent frame transmissions are contention-free. The AP can recognize the start and the end of a TXOP based on the information in the MAC headers of the received frames. In 802.11, a STA uses the *duration* field in the MAC header to reserve the channel. In our algorithm, the *duration* field of the transmitted frames is set to the time needed to finish the whole frame burst at the beginning of a TXOP and then reduced to the time needed to finish the subsequent transmissions during the TXOP. Therefore, by looking at the *duration* field, AP can easily know when a new frame burst starts and when it should count.

The limitation of the centralized algorithm lies in the scalability. Since the AP is responsible for advertising the TXOP limit assignments for each associated STA in the beacons, the large number of stations leads to a lot of overhead.

C. Distributed Temporal Fairness Algorithm

1) Algorithm: In the distributed algorithm, each STA measures its own share of channel occupation time and updates its TXOP after every MW. As in Fig. 6, we denote with $X_i[K]$ (K=0,1,…) the TXOP of STA i after its K-th TXOP adjustment. In the K-th MW, STA i measures its share of channel occupation time as:

$$\alpha_i[K] = \frac{T_i[K]}{T_{total}[K]} = \frac{NP_{si}X_i[K]}{T_{total}[K]} \qquad (3)$$

where $T_i[K]$ is the channel occupation time of STA i and $T_{total}[K]$ is the total channel occupation time of all M stations within the K-th MW.

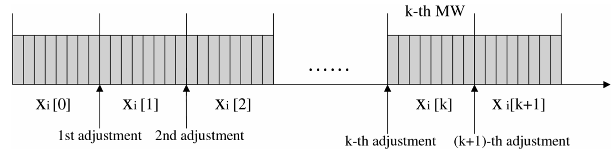


Figure 6. TXOP adjustment at station i: a new TXOP is calculated every MW

Based on the measurements in the K-th MW, STA i needs to determine its new TXOP, $X_i[K+1]$, at the end of the K-th MW. In our algorithm, STA i uses $T_{total}[K]$ as a rough estimate for $T_{total}[K+1]$ and predicts its share of channel occupation time in the (K+1)-th MW based on a linear prediction

$$\tilde{\alpha}_i[K+1] = \alpha_i[K] - \beta(\alpha_i[K] - \frac{1}{M}) \qquad (4)$$

where $1/M$ is the target ratio. $X_i[K+1]$ is then obtained from

$$\frac{NP_{si}X_i[k+1]}{T_{total}[k]} = \tilde{\alpha}_i[K+1] \qquad (5)$$

The distributed algorithm is shown in Table II.

TABLE II
DISTRIBUTED TEMPORAL FAIRNESS PROVISIONING ALGORITHM

At each station:
Variables: α, T_{self}, T_{total}, N_{self}, N_{total}, X, $T_{residue}$ Output: X_{new} *(calculated new TXOP)*

When it attempts to initiate a TXOP
$n := (X+T_{residue})/T_s$
$d_{rts} := T_{sifs}+T_{cts}+[n].T_s$
if it hears a CTS intended to itself //successfully obtains a TXOP
T_{self} += $T_{rts}+d_{rts}$
T_{total} += $T_{rts}+d_{rts}$
N_{self} ++
N_{total} ++
$T_{residue} := (n-[n]).\ T_s$
if it overhears a CTS not intended to itself:
T_{total} += $d_{cts} + T_{sifs} + T_{cts}+T_{rts}$
N_{total}++
if (N_{total} >= MW)
$\alpha := T_{self}/T_{total}$
$\alpha := \alpha - \beta * (\alpha - 1/M)$
$X := T_{total} * \alpha / N_{self}$
$N_{total} := 0$
$N_{self} := 0$

To measure its share of channel occupation time, a STA has to measure the total channel occupation time by all STAs and its own channel occupation time in the past measurement window. To facilitate the measurement of the total channel occupation time, each STA uses RTS/CTS/DATA/ACK four-way mode in our algorithm and exploit the *duration* field in the RTS/CTS frames. It should be noted that the RTS/CTS exchange only takes place at the beginning of a TXOP frame burst. Every time a station initiates a new TXOP, it calculates the time duration of the whole frame burst and set the *duration* field of the RTS to the calculated time duration. Recall that to avoid fragmentation, a STA releases the residual TXOP time for other STAs' use and rolls over the released time to its following TXOP. If we denote with $T_{residue}$ the residue time from last TXOP and X_{cur} the current TXOP allocation, the number of frames that STA i can transmit once it acquires the channel is

$$n_i = [\frac{X_{cur} + T_{residue}}{T_{si}}],$$

where T_{si} is the frame transmission time. The *duration* of the RTS frame is then set to $d_{rts} = T_{sifs}+T_{cts}+n_iT_{si}$. After receiving the RTS frame, the AP acknowledges with a CTS whose *duration* field is set to $d_{cts} = d_{rts}-T_{sifs}-T_{cts}$. Since all other STAs can hear the CTS from the AP, they update their NAVs based on the *duration* field accordingly, which ensures the contention-free transmissions of the following data frames in the TXOP. Upon hearing the CTS, a STA also increments the total number of the successfully acquired TXOPs and increase the total channel occupation time by $d_{cts}+T_{sifs}+T_{cts}+T_{rts}$ where d_{cts} is directly read from the *duration* field of the CTS.

2) Convergence Condition of the Distributed Algorithm:

Lemma 1: The distributed algorithm converges when $0 < \beta < 2$.

To show Lemma 1, we first rewrite (3) as

$$\alpha_i[K] = \frac{T_i[K]}{T_{total}[K]} = \frac{NP_{si}X_i[K]}{\sum_{j=1}^{M} NP_{sj}X_j[K]} = \frac{P_{si}X_i[K]}{\sum_{j=1}^{M} P_{sj}X_j[K]} \quad (6)$$

where $T_{total}[K]$ is written as the sum of channel occupation time of all M STAs. By combining (4), (5) and (6), we obtain the matrix form of the distributed algorithm

$$\mathbf{X}[K+1] = \left((1-\beta)\mathbf{I}+\frac{\beta}{M}\mathbf{A}\right)\mathbf{X}[K] \quad (7)$$

where $\boldsymbol{X}[K] = (X_1[K]\ \ X_2[K] \ldots X_M[K])^T$, $\boldsymbol{I}$ is an $M \times M$ identity matrix and

$$\mathbf{A} = \begin{pmatrix} \frac{P_1}{P_1} & \frac{P_2}{P_1} & \cdots & \frac{P_M}{P_1} \\ \frac{P_1}{P_2} & \frac{P_2}{P_2} & \cdots & \frac{P_M}{P_2} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{P_1}{P_M} & \frac{P_2}{P_M} & \cdots & \frac{P_M}{P_M} \end{pmatrix}$$

If we let $\mathbf{B} = (1-\beta)\mathbf{I} + (\beta / M)\mathbf{A}$, then the system is stable (and the algorithm therefore converges) if $|\lambda(\mathbf{B})| < 1$ or $|\lambda(\mathbf{B})| = 1$ but has multiplicity 1, where $\lambda(\mathbf{B})$ denote the eigenvalue of matrix $\boldsymbol{B}$. It can be shown that such stability condition is satisfied if and only if $|1-\beta| < 1$, that is, $0 < \beta < 2$ is the admissible region to ensure the convergence of the distributed algorithm.

3) Fragmentation Issue: Given that a STA always has frames to transmit, we can again enforce "no fragmentation" rule to avoid excessive fragmentation overhead in the distributed algorithm. The problem is to find a set of $\{X_i\}$, which leads to α=1/M and satisfies $X_i \geq T_{si}$ for any i, where T_{si} is the frame transmission time of STA i. The feasibility of this problem can be justified as follows. As shown above, with an appropriate choice of β, we can always obtain a solution, say $\boldsymbol{X_0}$, which solves (7). Multiplying $\boldsymbol{X_0}$ with any non-zero constant would also be a solution to (7). Therefore there always exists a C_0 such that when $C \geq C_0$, $C\boldsymbol{X_0} \geq T_{si}$ for any i.

To adjust TXOP, at the end of each measurement window, a STA calculates its new TXOP according to (5). However, if the resulting value is smaller than its frame transmission time T_{si}, the station sets the TXOP to be T_{si}.

Following the similar convergence analysis, we obtain the same admissible region of β as above, that is, the system is stable and the algorithm converges as long as $0 < \beta < 2$.

IV. Performance Evaluation

In this section, we present the simulation results to show the effectiveness of our proposed TXOP adaptation algorithms in providing temporal fairness in multi-rate WLANs with capture effect. We use the ns2 [14] framework, and extend the 802.11 module to include the TXOP operation. We assume 802.11b [9] as the underlying PHY and hence the basic rate set includes 1, 2, 5.5 and 11Mbps. In our model, each station in the network is the source of an elastic traffic flow, i.e., they always have backlogged frames to transmit. Unless specified otherwise, we use a constant frame size of 1052 bytes (including the MAC header) for each traffic flow. Under an AP, we vary the number of STAs to study the performance of the fairness provisioning schemes in the networks of different sizes. Network topology is randomly generated and all STAs can hear the AP.

We use a wireless channel model in which a STA's data rate depends only on its distance to the AP. Measurement window (*MW*) is chosen such that *MW*/*M*=400, where *M* is the number of STAs, i.e., on average each STA can transmit 400 frames during a *MW*.

A. Fairness Improvement

The first important metric in our study is fairness. In this paper, we use Jain's fairness index to measure the fairness performance. This index has been used widely in the literature to describe the fairness characteristics in both congestion control [15] and wireless MAC protocols [16]. It is defined as

$$F = \frac{(\Sigma T_i)^2}{M \Sigma T_i^2}$$

where M is the number of stations and T_i is the channel occupation time of station i. A perfectly fair system would result in a value of 1 for F. In practice, $F > 0.95$ is typically considered to indicate excellent fairness properties.

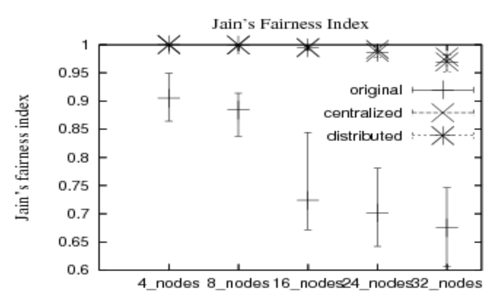


Figure 7. Fairness improvement using the proposed temporal fairness Schemes: both centralized and distributed algorithms can effectively enhance the fairness performance (Jain's index is close to 1)

We vary the number of stations to be 4, 8, 16, 24, and 32, respectively. For each network size, we randomly generate 15 topologies. We present the fairness index of the original 802.11 DCF and our proposed schemes in Fig. 7. Each bar in the figure reflects the mean and the span of the Jain's index across 15 topologies. Due to different topologies, the fairness index of the original 802.11 MAC could span a very large range. Our centralized and distributed algorithms can improve the fairness to around 1 with very small variations (the bar almost shrinks to a point). The results show that the proposed temporal fairness schemes can achieve fairness by dynamically adjusting TXOP to compensate for the capture effect.

B. *Throughput Improvement*

In this section, we study the impact of temporal fairness on the total throughput of the AP. We show the throughput increase over the original 802.11 DCF by using the proposed temporal fairness schemes in Fig. 8. Since the centralized and the distributed algorithms achieve almost the same throughput, we only plot the data from the distributed algorithm. We investigate the throughput in the networks of different size. We see that the total throughput is improved by 18%~35% while temporal fairness is achieved. This is because with temporal fairness, the stations with higher data rates get more channel time to transmit compared to the original 802.11 DCF.

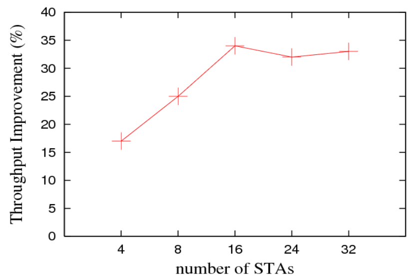


Figure 8. Throughput gain (%): time-based fairness improves the throughput performance by 18%~35 \%

C. *Algorithm Convergence*

Next, we study the convergence of the proposed algorithms. The faster the algorithms converge, the better fairness and throughput performance can be achieved. In Fig. 9, we show how the centralized and distributed algorithms converge with time. We see that in most cases, the centralized algorithm converges a little bit faster than the distributed method. This is because in the centralized algorithm, the AP has the global information of STAs' transmissions. Both algorithms converge faster for the smaller number of stations. For example, in the 4-station network, fairness reaches 0.9 at 5s in both algorithms, while in the 24-station network, fairness reaches 0.9 at 40s and 60s for the centralized and distributed algorithms, respectively.

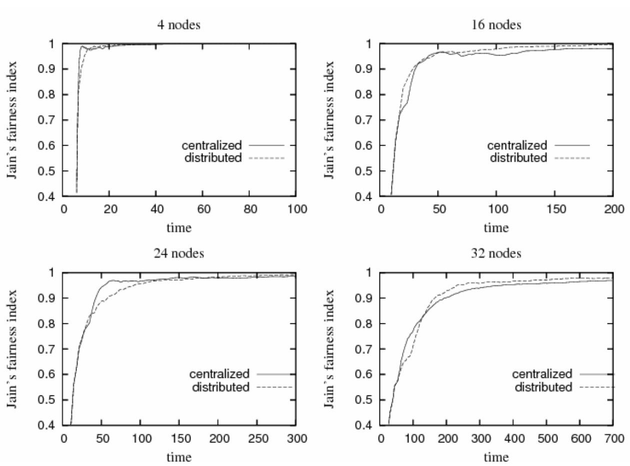


Figure 9. Convergence of centralized and distributed algorithms

V. Conclusions

In this paper we have shown that the physical layer capture effect causes significant imbalance in channel access opportunities, and subsequently, leads to unfairness among contending stations in wireless LANs. Temporal fairness is actually not held if each contending station simply uses an equal TXOP per channel access. We have proposed both the centralized and distributed TXOP adaptation algorithms to compensate for the impact of capture effect on the channel access opportunity so that temporal fairness can be achieved in multi-rate wireless LANs. Simulation results show the efficacy of the proposed schemes.

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