Contention Window and Transmission Opportunity Adaptation for Dense IEEE 802.11 WLAN Based on Loss Differentiation

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***Abstract*— In high density (HD) WLANs, packet losses can occur due to hidden terminals (asynchronous interference) or collisions (synchronous interference). Without differentiating above packet losses, the standard backoff algorithm of IEEE 802.11 with binary exponential backoff (BEB) can greatly degrade throughput and fairness. In this work, we exploit differentiated PER (packet error rate) to propose a novel CWTO (joint Contention Window and Transmission Opportunity) adaptation algorithm to improve the *aggregate throughput* as well as *network fairness* for multi-cell HD WLANs. Contention Window and Transmission Opportunity adaptation are dedicated to throughput maximization and fairness provision respectively and their effectiveness supported by extensive simulation results.**

***Index Terms*— WLAN, Contention Window (CW), Adaptation, Transmission Opportunity (TXOP), Loss differentiation**

I. INTRODUCTION

In recent years, IEEE 802.11 wireless LANs have gradually become the preferred technology for wireless Internet and Intranet access. Such large-scale WLAN deployments in enterprises, university campuses and public spaces (airports, shopping centers) typically involve a large number ($\sim 100s$) of Access Points (APs) that may be separated by only a few meters [1]. This creates a multi-cell backbone network - a High Density Infrastructure WLAN - to serve an increasing number of simultaneous clients ($\sim 1000s$). However, because of the small number of non-interfering channels available for 802.11 in the unlicensed bands, such multi-cell WLANs are interference limited. In our previous work [2], we studied on-line adaptation of carrier sense range for improving the aggregate throughput of a HD WLAN using effective loss differentiation. In this work, we continue our efforts by investigating the role of joint CW and TXOP adaptation in enhancing aggregate throughput.

IEEE base MAC in 802.11 adopts a slotted binary exponential backoff (BEB) algorithm to avoid collisions. The algorithm assumes that all losses are caused by collisions (contending stations within carrier sensing area transmit in the same slot) and doubles the contention window (CW) size to reduce contention upon a frame loss. However, in a HD WLAN, the losses due to hidden terminal (apart from collisions) may also be significant, because of the interference arising from secondary sources in a different BSS. Thus, standard BEB algorithm will cause unnecessarily long delay, poor channel utilization [6] and worsen the long-term fairness[7]. Furthermore, recent studies [7][8] show that an appropriate choice of a *fixed* CW size nearly approaches the throughput performance of BEB in both single cell and multi-hop WLANs. Rather, BEB worsens short-term fairness even in the absence of any hidden terminals. Therefore, in this work, we will turn off BEB and only adapt the “fixed” CW value of each station.

We therefore propose a CWTO (*joint Contention Window and Transmission Opportunity*) adaptation algorithm to improve the aggregate throughput as well as network fairness for multi-cell WLANs. Although Contention Window alone can be used also for fairness provision[9], we show that tuning TXOP (Transmission Opportunity) rather than CW should be the preferred option for fairness. In order to adapt to topology differences and traffic variation, the algorithm will adjust the CW values of each link according to the node density and instantaneous *differentiated PER (packet error rate) due to collisions only*. The loss differentiation method has already been developed and reported in our previous work [11]. Meanwhile, TXOP control will provide network fairness with best effort. Thus CWTO can effectively accommodate differences in network topology, nonhomogeneous node density and traffic variation. In addition, CWTO algorithm does not need any topology information and can be widely used in both 802.11 HD infrastructure and ad-hoc mesh networks.

II. BENEFIT OF JOINT CW AND TXOP ADAPTATION

In this section, we demonstrate the benefit of joint CW and TXOP adaptation via an analytical model. In [9], the authors proposed a novel continuous time Markov chain model to derive link throughput in multi-hop ad-hoc WLANs. In this paper, we will extend the above model to include TXOP and assess its impact. In addition, we will apply the extended model to the well-known 3-pairs scenario [9], shown in Fig. 1, to demonstrate the advantage fairness provisioning via TXOP control rather than CW control.

In the 3-pairs network, two links (A and C) are out of both the carrier sensing range and interference range of each other and thus not coordinated. Such cases provide simple canonical examples of known significant fairness problems.

This work was supported in part by Intel Corp.

When all links are backlogged, the middle one achieves very low throughput because it can capture the medium only when *both* outer links are in the back-off phase. Next, we select CW and TXOP as the control parameter for fairness provision and compare the network throughputs for these two solutions when the three pairs achieve the equal channel access time.

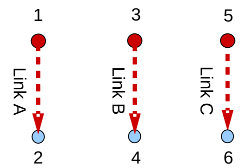

Fig. 1. A 3-pair WLAN

Transmission Opportunity, originally proposed in the IEEE 802.11e standard, defines a period of time that a 802.11 device can use for successive transmissions with a single channel access, limited by $TXOP_{limit}$ [1]. After a successful frame transmission, indicated by reception of an acknowledgement(ACK), a continuation of TXOP is granted to transmit another frame. Therefore, TXOP is an effective tool for fairness since it allows a node with lower channel access probability, a larger TXOP duration.

In [9], it is shown that by ignoring any collision overhead, the throughput of the three links operating with equal channel data rate C in Fig. 1 is given by

$$\begin{cases} x_A = \frac{\rho_A + \rho_A\rho_C}{1+\rho_A+\rho_B+\rho_C+\rho_A\rho_C} \cdot C \\ x_B = \frac{\rho_B}{1+\rho_A+\rho_B+\rho_C+\rho_A\rho_C} \cdot C \\ x_C = \frac{\rho_C + \rho_A\rho_C}{1+\rho_A+\rho_B+\rho_C+\rho_A\rho_C} \cdot C \end{cases} \quad (1)$$

and ρ_i $(i = A, B$ or $C)$ is the scheduling rate of a link, which is modified from (12) in [9], given by

$$\rho_i = \frac{2L \cdot TXOP_{limit_i}}{CW_i \cdot C \cdot T_{slot}} \quad (2)$$

wherein $TXOP_{limit_i}$ is a new term introduced to capture the effect of TXOP[2] of link i, CW_i is the fixed contention window size of link i, L is the data frame size, and T_{slot} is the duration of a slot time.

In the analysis, we assume CW of links A and C are identical and denoted as CW_A and their $TXOP_{limit}$ equals 1. For equal link rates, time fairness (all links share the channel equally) is appropriate for which it suffices that $x_A = x_B$[3]. We first find the $TXOP_{limit}$ or CW (denoted as $TXOP_B$ or CW_B) of the link B satisfies above condition. Then we estimate the total collision overhead, $Loss_{coll}$ by

$$Loss_{coll} = 2L * \frac{x_B}{TXOP_B \cdot L} \cdot \left(1 - (1 - \frac{2}{1+CW_A})^2\right) \quad (3)$$

where $\frac{x_B}{TXOP_B \cdot L}$ represents the frequency at which Link B initiates channel access, $1 - (1 - \frac{2}{1+CW_A})^2$ is the collision rate for such channel access and $2L$ represents the two frame losses in each collision event.

[1]For convenience, instead of using time duration, we define $TXOP_{limit}$ as the number of permitted successive transmissions.

[2]Setting $TXOP_{limit}$ equal to 1 disables it.

[3]Due to symmetry of link A and C, $\rho_A = \rho_C$ and hence $x_A = x_C$.

Finally, by excluding the collision overhead, we can determine the aggregate throughput TH of the network by

$$TH = x_A + x_B + x_C - Loss_{coll} \quad (4)$$

With $C = 6Mbps$ and $T_{slot} = 9\mu sec$ for 802.11a, the equality $x_A = x_B$ can be met either via a suitable CW_B (CW control with $TXOP_B = 1$) or suitable $TXOP_B$ (TXOP control with $CW_B = CW_A$). The corresponding TH and $Loss_{coll}$ for the two solutions as a function of packet size L and CW_A are shown in Fig. 2.

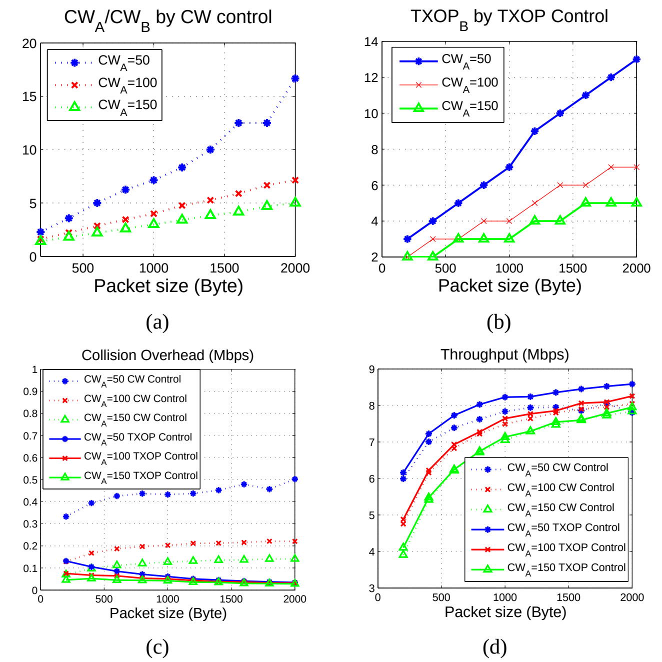

Fig. 2. CW vs TXOP control for fairness in 3 contending flows

With increasing L for any fixed CW_A, the time fairness is more difficult to achieve, i.e. Link B needs a smaller CW_B or a larger $TXOP_B$. For example, when $L = 2000\, bytes$ and $CW_A = 50$, CW_B has already decreased to 3. Such a value is too small and not practical in a WLAN, because it can produce substantial collisions if station 4 also has data to send. Therefore with CW control for fairness, even the stations in favored positions (such as station 1 and 5) may have to use a relatively high CW (such as 100), leading to many unnecessary idle slots and low channel utilization. In contrast, TXOP does not have this limitation. In addition, for each CW_A, collision overhead of TXOP control is much lower than that of CW control, because frame bursts in TXOP could reduce collisions. Therefore TXOP control achieves a higher throughput, especially when CW_A value is small.

In summary, fairness provisioning via TXOP control in a multi-hop WLAN is the preferred alternative as it (a) allows stations to operate with more pragmatic CW values and (b) reduces collisions. These motivate a joint adaptation algorithm in the next section, where CW and TXOP will be dedicated to throughput maximization and fairness provisioning respectively.

III. Joint CW and TXOP adaptation algorithm based on loss differentiation

The proposed CWTO algorithm has three components: i) estimation of the number of competing stations, ii) CW adaptation and iii) TXOP adaptation. The first component is the basis of CW adaptation, and the rest two are in charge of throughput maximization and fairness provision.

A. Estimation of the number of competing stations

The first step toward an efficient adaptation framework is the estimation of the number of competing stations (denoted as M_i) around any reference station i; then each station can set its CW size according to the "node density" around it. The previous estimators of the number of competing stations for single-cell networks (e.g. [5]) assume stations are all within one carrier sensing range and hence all synchronized. Clearly, this is not true for multi-cell WLANs; we next propose a novel method to estimate M_i based on only the activity of carrier sensing.

In a multi-cell WLAN, M_i denotes the total number of active stations within the carrier sensing range of station i (including i itself); therefore M_i depends on the value of PCS (Physical Carrier Sensing) threshold (γ_{cs}) used in a network. We introduce $P_b(i)$, defined as the probability that at a slot boundary, the channel around a reference station i is busy due to the transmission by one or more other stations within the carrier sensing range. The measurement of $P_b(i)$ is based on synchronizing all stations by forcing them to use a low PCS threshold, γ_{min} [4]. In addition, stations use a constant large CW size(denoted by CW, say 1023) and measure the following two variables:

- n_i: the number of slots in which the reference station i does not transmit;
- m_i: within the above n_i slots, the number of *busy* slot whose energy level measured is higher than γ_{cs}.

Thus the estimator $< P_b(i) >$ [5] is m_i/n_i. Further, when $M_i - 1$ stations contend for the channel along with the reference station i, the true $P_b(i)$ for the reference station is given by

$$P_b(i) = 1 - (1-\tau)^{M_i - 1} = 1 - (1 - \frac{2}{1+CW})^{M_i-1} \quad (5)$$

where τ is the transmission probability for each station. For fixed CW, $\tau = 2/(1+CW)$[4]. Then we can estimate the number of competing stations around each station by

$$M_i = \frac{log(1-\frac{m_i}{n_i})}{log(1-\frac{2}{1+CW})} + 1 \quad (6)$$

B. Centralized CW adaptation for throughput optimization

In the proposed CW adaptation algorithm, the contention window size used by each station is proportional to its M_i value. In this way, stations in dense(sparse) area will use a large(small) CW value, a solution that can minimize the collision probability of all stations simultaneously. To be *adaptive to traffic variation*, a central controller tunes the value of $CWratio$ (the ratio between CW and M) periodically, searching for the optimal $CWratio$ (maximize aggregate throughput) while satisfying the maximum PER (collision) constraint on each link. Then each station i sets its contention window size (CW_i) according to its M_i value, i.e.

$$CW_i = M_i \cdot CWratio \quad (7)$$

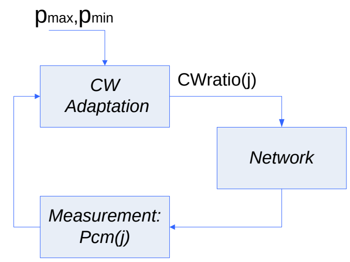

Fig. 3. The block diagram of CW adaptation

A schematic block diagram of CW adaptation is shown in Fig. 3 and we define the following:

- j: iteration index corresponding to CW updating period
- T: CW updating period
- $P_{cm}(j)$: the **highest** differentiated PER due to collisions within jth updating period
- p_{min}, p_{max}: targeted minimum, maximum collision probability
- $CWratio(j)$: $CWratio$ used after jth CW update update
- δ: $CWratio$ adaptation step

In the adaptation, instead of using the total PER (packet error rate) of the links, we use the differentiated PER due to collisions as the constraint. In a HD WLAN, the packet losses due to hidden terminals (apart from collisions) cannot be ignored (even with optimal γ_{cs} [2]) and thus using the total PER will lead to unnecessarily large CW values, resulting in lower throughput. Clearly, the above adaptation presumes effective loss differentiation method as developed in our previous work [11]: in particular, using measured energy and delayed sensing, each station separately estimates the PER due to collisions and hidden terminals in real time as described there [6]. Furthermore, for adaptation stability, an exponentially smoothed moving average with a 0.5 smoothing factor is used to smooth the measurement of PER due to collisions. At the end of an updating period, all stations report its smoothed PER due to collisions to a node identified as a 'central controller'. Among these reported PER due to collisions, the **highest** differentiated PER $P_{cm}(j)$, will be used to adapt the $CWratio$, to accommodate traffic variation for the next updating period, as follows:

$$CWratio(j) = \begin{cases} CWratio(j-1) + \delta & \text{if } P_{cm}(j) > p_{max} \\ CWratio(j-1) - \delta & P_{cm}(j) < p_{min} \\ CWratio(j-1) & \text{otherwise} \end{cases} \quad (8)$$

In order to maximize the throughput, the setting of an appropriate target collision probability is desired; it should

[4] γ_{min} is much lower than the actual operational PCS threshold γ_{cs}.

[5] We use $< >$ around $P_b(i)$ to denote its estimate based on observed data.

[6] With TXOP, PER estimation for collisions are only performed for the first transmission in each frame burst.

balance the tradeoff between idle slots and collisions resulting from simultaneous transmissions, both of which results in reduced throughput. We set this target value according to results derived by [3]. The equation (28) in [3] shows the optimal transmission probability τ_{opt} in the single-cell network as a function of the number of stations n and packet size, i.e.:

$$\tau_{opt} = \frac{\sqrt{[n + 2(n-1)(T_C^* - 1)]/n} - 1}{(n-1)(T_C^* - 1)} \tag{9}$$

where T_C^* is the duration of a collision measured in slot time unit.

Thus the collision probability for the τ_{opt} in the single-cell network is given by

$$P_{copt} = 1 - (1 - \tau_{opt})^{n-1} \tag{10}$$

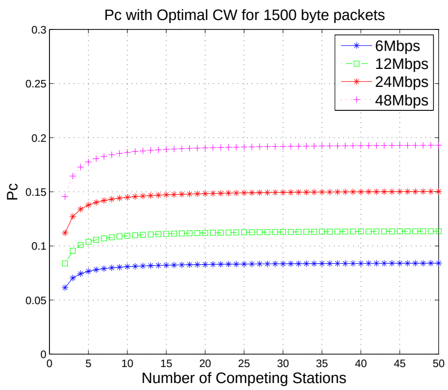

Fig. 4. Collision probability with optimal CW as a function of number of stations and link data rate

We show P_{copt} for 1500 bytes packets as a function of 802.11a link data rate and n in Fig. 4. Interestingly, as n increases, the P_{copt} for each data rate is relatively flat for different n. Thus the converged value of P_{copt} can be used as the target collision probability for a network with variable node density. In particular, we set p_{min} to be the converged value of P_{copt} and p_{max} to be slightly higher than p_{min} to avoid oscillation in the adaptation. The effectiveness and robustness of such setting will be evaluated in simulations.

C. Distributed TXOP adaptation for fairness

The goal of fairness tuning by TXOP is to guarantee that the *worst* link throughput is higher than some preset threshold. We did not provide max-min fairness in this work, because they inevitably require more overhead by way of information exchange to acquire network topology. A schematic block diagram of TXOP adaptation is shown in Fig. 5.

The algorithm adopts a best effort approach without information exchange, where each link tries to use a suitable TXOP value to make its Tx (the number of frame transmissions per second) for each updating period higher than a preset threshold, TH_{Tx}. TH_{Tx} can be configured by the hardware vendor or an IT manager, which will be set adaptively according to Quality of Service (QoS) requirement and network density. Once a link's Tx value is lower than TH_{Tx} in a period, it will increase its $TXOP_{limit}$ by 1 until it reaches the upper limit $TXOP_{max}$ (say 10). Once Tx is higher than TH_{Tx} for a number (say 5) of consecutive periods, it will decrease its $TXOP_{limit}$ until it reaches 1.

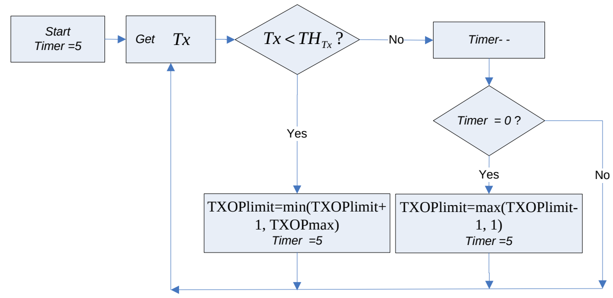

Fig. 5. The block diagram of TXOP adaptation

IV. Simulation Evaluation

We next evaluate the performance of the proposed CWTO solution by OPNET simulation. The simulations are carried out in OPNET v.11 using the modified physical carrier sensing module developed in [12]. TXOP mechanism is further developed in the above model. We use the aggregate throughput to measure system capacity, and use worst link throughput and Jain's fairness index [10] to measure fairness. Two network topologies are investigated: a) A 20-cell random annular WLAN; b) A 25-cell random cellular WLAN. Each scenario will be evaluated with CWTO and the legacy algorithm(BEB with $CWmin = 15, CWmax = 1023$) for comparison. For simplicity, all cells in each scenario are assumed to work on a single channel and all traffic are saturated flows with a constant packet size of 1500 bytes.

The simulation was conducted for 802.11a band with transmit power of 25mW, link data rate of 24Mbps and path loss exponent of 2. To average the PER, T is set to 10 sec. The reception sensitivity was set such that the reception range was 10 m; thus a receiving station can only receive packets up to a maximum distance of 10 m. The PCS threshold γ_{cs} for the two scenarios was set to -68.3dBm and -69.3dBm respectively,which are the optimal values found by the PCS adaptation algorithm proposed in our previous work[2] to maximize spatial reuse. γ_{min} was set to -82.8dbm. As for CW adaptation, we set the target PER ranges such as $(p_{min}, p_{max}) = (0.15, 0.17)$ according to Fig.4, and set $\delta = 0.5$ and initial $CWratio = 15$. Each simulation duration was 600 sec., i.e. 60 CW updating periods. All the performance metrics are collected over a 100 sec. duration post adaptation to accurately measure network performance.

TABLE I
CW and TXOP adaptation in a 20-cell random annular WLAN

	Aggregate Throughput	Worst Link Throughput	Fairness Index
Legacy	39.9 Mbps	287.8 Kbps	0.633
CWTO(10%-12%)	51.8 Mbps	589.8 Kbps	0.766
CWTO(15%-17%)	51.8 Mbps	555.8 Kbps	0.753
CWTO(20%-22%)	51.3 Mbps	547.7 Kbps	0.746
CW only(15%-17%)	49.3 Mbps	397.3 Kbps	0.709

First, we study a random annular WLAN, which consists of 20 cells with cell radius of 10 meters and AP-to-AP distance of 20 meters. Each cell has a *random* number of clients (1 to 5, thus the network is nonhomogeneous) located at the cell boundary and each client transmits saturated traffic to its AP. TH_{Tx} is set to 50 frames/second. The purpose of this simulation is to show how CWTO performs in relatively symmetric network. In this experiment, we also study the robustness of proposed (p_{min}, p_{max}) setting by adding or subtracting 5% from the proposed values.

Table I shows the results of three metrics respectively. The numbers in the brackets are different targeted (p_{min}, p_{max}). Firstly, CWTO achieves much higher aggregate throughput than "Legacy", i.e. there is 30% throughput improvement for targeted range $(15\% - 17\%)$. This improvement mainly comes from the reduced collisions via CW adaptation, which can be validated by an experiment without TXOP adaptation, labeled by "CW only". The throughput of "CW only" is close to that of CWTO, showing that up to 80% of above throughput improvement can be attributed to CW adaptation only. Secondly, CWTO greatly improves fairness: worst link throughput doubles and fairness index increases from 0.633 to 0.753. Finally, the performances for the three targeted (p_{min}, p_{max}) with a difference up to 10% are very close, indicating that the performance of CWTO is not quite sensitive to the value of the targeted collision probability. This implies one common (p_{min}, p_{max}) may be applied to a network with more diversified packet sizes.

TABLE II

CW AND TXOP ADAPTATION IN A 25-CELL RANDOM CELLULAR WLAN

	Aggregate Throughput	Worst Link Throughput	Fairness Index
Legacy	46.5 Mbps	47.8 Kbps	0.426
CWTO(15%-17%)	45.8 Mbps	457.9 Kbps	0.727

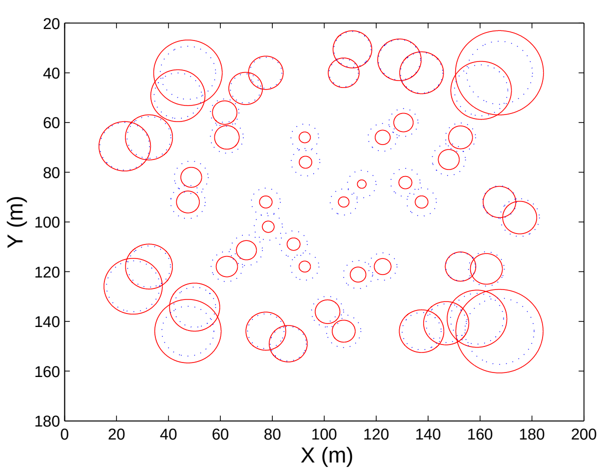

Fig. 6. Link throughput in a 25-cell random cellular WLAN. The area of solid (red) and dotted (blue) circles represent the throughputs of all 50 individual links for "Legacy" and CWTO respectively.

Second, a more practical dense WLAN deployment scenario is studied. It comprises 25 co-channel cells in a hexagonal layout with cell radius of 10 meters and AP-to-AP distance of 30 meters. Each cell has one AP and one client (STA), and both AP clients are transmitting saturated traffic, i.e. a total of 50 links in the network. TH_{Tx} is set to 40 frames/second.

Table II shows the simulation results. CWTO dramatically improves fairness: worst link throughput increases by more than 8 times and fairness index increases from 0.426 to 0.727. At the same time, CWTO still can achieve almost the same throughput as "Legacy". We also show all the individual link throughputs in Figure 6. Comparing with "Legacy", the throughput of all links in the middle have been greatly improved by CWTO. This throughput distribution indicates why there is no improvement in aggregate throughput in this experiment. It results from the familiar trade-off between throughput and fairness in a multi-hop network: letting the center links transmit one more packet may prohibit two or more simultaneous transmissions on the edge. However, CWTO can achieve much better fairness than "Legacy" with almost the same throughput confirming its effectiveness.

V. Conclusion

In this work, we proposed a joint Contention Window and TXOP adaptation algorithm, CWTO, to improve the aggregate throughput and network fairness for dense multi-cell WLANs. CW is adjusted according to the instant differentiated PER due to collisions; while TXOP control provides network fairness with best effort. The simulation results quantify the achievable aggregate throughput, worst link throughput and fairness index. Future work will consider approaches for distributed CW adaptation and study how the value of $TXOP_{limit}$ impacts network access delay.

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