Contention Window Adjustment for IEEE 802.11 WLANs: A Control-Theoretic Approach

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***Abstract*— IEEE 802.11 is currently the most popular standard for Wireless LANs. The Distributed Coordination Function (DCF) defines the primary medium access control of 802.11, which uses the CSMA/CA mechanism and Binary Exponential Backoff (BEB) for Contention Window (CW) adjustment when collisions occur. In this paper, we propose a new CW adjustment scheme, CW Idle-Slots-based Control (WISC), using a control-theoretic approach. Specifically, we design and implement a PD (Proportional and Derivative) controller at each contending station, that dynamically adjusts CW based on a locally available channel state, i.e., the average number of consecutive idle slots between two transmissions, such that the channel state converges to the optimal value. Simulation results demonstrate that the new scheme outperforms the standard BEB in terms of both throughput and fairness, especially at high contention levels.**

I. INTRODUCTION

In recent years, Wireless Local Area Network (WLAN) technology has evolved at a rapid speed. Most of the commercial WLAN products are based on the IEEE 802.11 standards [1]–[4], which define both the Medium Access Control (MAC) layer and the Physical (PHY) layers. The primary access mode of the MAC layer is implemented in the Distributed Coordination Function (DCF) using the Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA) mechanism. All stations compatible with the 802.11 standard are able to perform carrier sensing and can observe activities taking place on the channel. Before transmission, each competing station defers its attempt to access the channel a random time to avoid collisions. Specifically, it sets up a backoff timer according to a random backoff time chosen uniformly between 0 and the current Contention Window (CW) size, which is controlled by the Binary Exponential Backoff (BEB) algorithm in the DCF.

The contention window decides the frequency and order of the channel access and therefore performs a critical role in both channel utilization and fairness of bandwidth share among stations. There has been extensive work on CW control for improving the performance of the DCF in the literature [5]–[15]. Based on these works, in this paper, we elaborate our approach by explicitly designing a feedback control system with a PD (Proportional Derivative) controller from a control-theoretic standpoint, for CW Idle-Slots-based Control (WISC). The objective is to design a mechanism that maximizes the channel utilization. It should respond quickly to varying contention levels while maintaining excellent short time fairness. In the feedback control system, the reference value, i.e., the target channel state I_m, is defined as the average number of consecutive idle slots between two transmissions, which is asymptotically optimal (optimal when the number of active stations is large). Each station adjusts its own CW based on $I(t)$, the average number of idle slots observed locally. As a result, the network automatically converges to the optimal channel utilization asymptotically. We study the feedback control system performance (steady state error, stability, etc.), for assigning the proper values to the controller gains.

The rest of the paper is organized as follows. In section II, we briefly review the IEEE 802.11 DCF with CSMA/CA and BEB, followed by some other proposals. The details of our control-theoretic model and controller design are presented in section III, with an emphasis on how the proposed method meets our design objectives. Performance evaluation and numerical results of our proposed method are discussed in section IV. Finally, section V concludes our work.

II. RELATED WORK

A. IEEE 802.11 DCF

The mandatory DCF of the 802.11 standard provides distributed, contention-based access to the wireless medium. There are two access modes defined in the DCF, the basic access mode and the optional RTS/CTS (Request To Send/Clear To Send) access mode. In the basic access mode, before starting a frame transmission, each station checks the medium status by carrier sensing. If the medium is idle for longer than DIFS (DCF Inter Frame Space), the transmission may proceed immediately; if the medium is sensed busy, the station defers its transmission until the medium is determined to be idle for DIFS and the BEB procedure is invoked. While the medium stays idle, the backoff timer is decreased by one slot time for each backoff slot. The frame is transmitted when the timer reaches zero. Otherwise, the backoff procedure is suspended and is resumed after the channel is idle for DIFS. In this paper, we focus our discussion on the basic access mode.

In BEB, the random backoff timer is calculated by:

$$BackoffTimer = Random() * aSlotTime,$$

where $Random()$ is a pseudo-random integer drawn from a uniform distribution over the interval of $[0, CW]$, where

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$CW = 2^m - 1$ and $CW \in [CW_{Min}, CW_{Max}]$. The BEB procedure for CW adjustment is summarized below:

- Initially, all stations have $CW = CW_{Min}$.
- Experience a transmission success / exceed the retry limit:

$$CW = CW_{Min};$$

- Experience a transmission collision:

$$CW = min(2(CW+1)-1, CW_{Max}),\ i.e.,$$

$$CW = min(2^m(CW_{Min}+1)-1, CW_{Max}),$$

where $m = 1, ..., RetryLimit$.

B. Other Related Work

Lots of work in the literature has investigated CW dynamic tuning to gain performance improvement over BEB [5]–[13]. However, some can only achieve a satisfying performance under certain conditions; others, though theoretically optimal, are too complicated for a practical implementation.

Since the CW reset scheme of BEB may lead to unnecessary collisions and retransmissions when the contention level has not dropped, in [5], MILD (multiplicative increase linear decrease) CW adjustment scheme was introduced to solve this problem: a node increases its CW by multiplying it by 1.5, and decreases it by 1 upon a success. It also includes a CW copy mechanism to address the fairness issue. By smoothing the CW decrease, this scheme performs well when the network load is heavy. However, when the number of active stations changes sharply from high to low, MILD cannot adapt fast enough because of "linear decrease". Several similar schemes were proposed after MILD, including EIED [6], LMILD [7], MILMD [8], and SD [9]. All these schemes aim at making the CW oscillate around the optimal value without complicated runtime estimation; they only differ in linear / multiplicative increase / decrease factors.

In [10], the authors developed a p-persistent IEEE 802.11 protocol which closely approximates the standard protocol. Based on this, an analytic model is derived to study the theoretical capacity limit of the p-persistent protocol and compute the optimal p that maximizes the capacity. However, this requires an estimation of the number of active stations. Alternatively, Asymptotically Optimal Backoff (AOB) is proposed in [16], which measures the network contention level by two estimates: the slot utilization and the average size of transmitted frames. AOB adopts a CW size that maximizes the channel utilization. A transmission already enabled by BEB is postponed by AOB in a probabilistic way, which depends on the network congestion level.

Two novel approaches, *Idle Sense* [14] and GCA [15] have been proposed recently. With *Idle Sense*, each station observes I, the average number of idle slots between two consecutive busy slots. It then relies on the AIMD adjustment of CW according to an estimator of I. Without using collision as a signal to decrease transmission attempts, *Idle Sense* can decouple collision detection from load control. In [15], GCA (General Contention window Adaptation) is designed to decompose the requirement for both fairness and efficiency to the problem of choosing proper utility functions and functions of observable channel states, in order to achieve arbitrary bandwidth allocation and efficient channel utilization. Similar to *Idle Sense*, GCA identifies the optimal stable point that maximizes channel utilization, and provides solutions to control the stable point of GCA near the optimal point. Our work here can be viewed as a further exploration and improvement based on these two papers. We also identify the optimal channel state but adopt much stronger control over CW.

III. CONTROL-THEORETIC CW ADJUSTMENT

In this section, we first identify the optimal channel state maximizing the channel utilization, based on previous works [17], [14] and [15]. Then, we give a brief introduction to the feedback control theory and describe the PD controller used in our CW Idle-Slots-based Control (WISC) in detail. We adopt a uniform backoff scheme such that all stations in the same group share the same CW. Moreover, we assume ideal channel conditions such that each station operates at the IEEE 802.11b 11Mbps. The impact of the assumption are discussed at the end of this section.

A. The Optimal Channel State

There are two main factors that reduce the channel utilization: time spent in collided transmissions and following retransmissions; and idle backoff slots before data transmission. The optimal operating point can be found at the best tradeoff between these two factors. Note that our scheme should also avoid estimating the exact contention level (the number of active stations), but use locally available information which can reflect the load intensity of the channel. Similar to the observations in [14] and [15], we represent the optimal channel state I_m, by the average number of idle slots between two transmissions when the number of active stations is large. With this target quasi-constant I_m, we can design the control logic that drives the channel state to this optimal stable point. We provide a brief description of how to derive I_m below; the details can also be referred to [14] and [15]. Denote the attempt probability in a slot by τ, and if there are N contending stations, the average throughput $TP(\tau)$ can be expressed as:

$$TP(\tau) = \frac{P_S L_D}{P_S T_S + P_I T_{SLOT} + P_C T_C} = \frac{L_D}{T_S + \frac{P_I T_{SLOT} + P_C T_C}{P_S}} \quad (1)$$

where L_D is the average data frame length;
$P_I = (1-\tau)^N$ is the probability of an idle slot;
$P_S = N\tau(1-\tau)^{N-1}$ is the probability of a successful transmission in a given slot;
$P_C = 1 - P_S - P_I = 1 - (1-\tau)^N - N\tau(1-\tau)^{N-1}$ is the collision probability in a slot;
T_{SLOT} is the duration of an empty slot time;
T_S is the average successful transmission duration;
T_C is the average collision duration. For basic access mode,

$$T_C = PHY_{ov} + \lceil \frac{MACov + Payload}{BpS} \rceil + PropDelay + DIFS \quad (2)$$

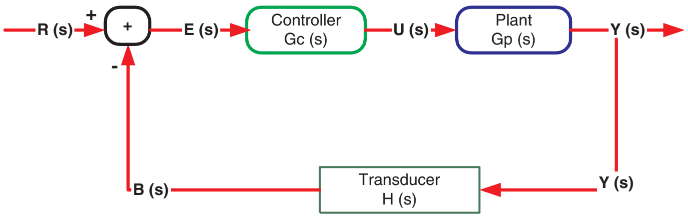

Fig. 1. Feedback control system.

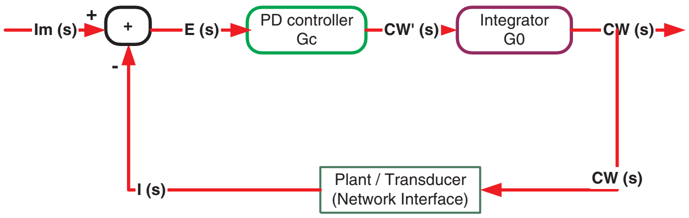

Fig. 2. CW Idle-Slots-based PD control system.

To maximize the average throughput in (1), it is equivalent to minimize

$$C(\tau) = \frac{P_I T_{SLOT} + P_C T_C}{P_S} \tag{3}$$

The minimum of (3) can be found by setting $C'(\tau) = 0$:

$$1 - N\tau^* = (1 - \frac{T_{SLOT}}{T_C})(1-\tau^*)^N \tag{4}$$

Denote $\rho = N\tau^*$, (4) can be rewritten as:

$$1 - \rho = (1 - \frac{T_{SLOT}}{T_C})(1-\rho/N)^N \tag{5}$$

When $N \rightarrow \infty$, (5) becomes:

$$1 - \rho_\infty = (1 - \frac{T_{SLOT}}{T_C})e^{-\rho_\infty} \tag{6}$$

(6) can be solved numerically to get ρ_∞, and when $N \rightarrow \infty$,

$$P_I^* = (1 - \frac{\rho}{N})^N \rightarrow P_{I\infty}^* = e^{-\rho_\infty} \tag{7}$$

Therefore, the optimal average number of idle slots between two transmissions can be computed as:

$$I = \frac{P_I}{1-P_I} \rightarrow I_m = I_\infty^* = \frac{e^{-\rho_\infty}}{1-e^{-\rho_\infty}} \tag{8}$$

Note that I_∞^* is dependent on the PHY/MAC parameters and the frame size (to calculate T_C by (2)). For 802.11b (11 Mbps), basic access, and maximum frame size (1500 Bytes), $I_\infty^* \approx 5.68$ [14]. In practice, a set of target values can be pre-computed and one of them is selected according to the current network configuration (PHY mode, frame size, etc.).

B. CW Idle-Slots-based Control

Recently, there is a growing interest in applying control theoretic methods to analyze and design adaptive networking mechanisms [18], for both steady state and transient performance goals. Fig. 1 shows the basic structure of a feedback control system, which consists of a plant to be controlled, a controller, and a transducer. There are three basic control-related variables, the reference value $r(t)$, controlled variable $u(t)$ and measured variable $y(t)$. The measured variable is the quantity of the system output that is measured and to be controlled. The reference value represents the target value of the measured variable. The controlled variable is the system attribute that is dynamically modified by the controller so as to affect the value of the measured variable. The controller input $e(t)$, is defined as the error between the reference value and the current value of the measured variable ($e(t) = r(t) - b(t)$), where $b(t) = H[y(t)]$ is the current value of the measured variable $y(t)$ after some transformation H. The closed-loop system continuously monitors and compares $b(t)$ with $r(t)$ to determine $e(t)$; the controller changes the value of the manipulated variable $u(t)$ to control the system output $y(t)$ by using the control algorithm G_c and the current error $e(t)$.

The Proportional Integral Derivative (PID) controller is a simple and effective feedback control function. As the name suggests, it consists of the Proportional mode, the Integral and the Derivative modes, with the controller gains K_p, K_i and K_d respectively. When utilizing this algorithm, it is necessary to decide which modes are to be used (P, PI, PD or PID) and then specify the parameters for each mode used. Generally, the P control reduces error but does not eliminate it, the I control improves steady state errors, and the D control may improve stability and transient response. The PID control function can be described using the following formula:

$$u(t) = K_p \cdot e(t) + K_d \cdot \dot{e(t)} + K_i \cdot \int e(t) \tag{9}$$

Rewrite (9) in frequency domain by Laplace Transform:

$$U(s) = K_p + K_d \cdot s + K_i/s \tag{10}$$

In this paper, we use the PD controller ($K_i = 0$) for CW Idle-Slots-based Control, since it is already good enough to satisfy our design objectives. The resulting control system is illustrated in Fig. 2. The plant keeps on monitoring and comparing error between the currently sensed consecutive idle slots $I(t)$ and the target idle slots I_m. The time unit index t here for updating CW is the period for each packet transmission. Based on the resulting error $e(t)$ and the control function G_c, $\Delta CW(t)$ is calculated as $\Delta CW(t) = G_c[e(t)]$. Note that we do not use the PD controller to calculate the next $CW(t+1)$ value directly, since it is better to put a limit on the maximum value CW can be changed in one step .

The feedback information $I(t)$ is needed to reflect the network dynamics and predict the traffic load so as to support a high channel utilization. The running $I(t)$ results from not only the current $CW(t)$ used by contending stations but also the number of contending stations. Therefore, the proposed CW Idle-Slots-based feedback control must adapt to variations of these factors. We present our methodology in the next section in detail. Different from the standard BEB and its variants, which are collision triggered and adjust CW upon a collision, our approach adjusts CW whenever a transmission occur on the channel. The advantage of our approach is that idle slots

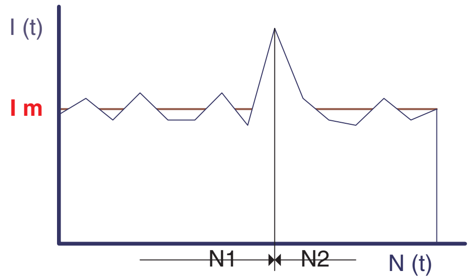

Fig. 3. Dynamics of the average number of consecutive idle slots.

information is readily available, since each station is aware of the channel activity by carrier sensing; also the adjustment is more timely and accurate, since it does not wait until a collision occurs and is independent of whether it is a collision failure or a channel error. More precisely, the only state a station distinguishes is busy or not, which comes for free with IEEE 802.11. No effort is required for collision detection.

C. Controller Design Methodology

In this section, we introduce how to model our feedback control system and assign proper PD controller gains satisfying design goals. We begin with the extreme case that there is only one active sending station in the WLAN. Therefore, when a station senses no activities from others (i.e., the backoff timer is never paused) for sufficient time in the steady state, it sets CW to CW_1, a much smaller value than the default CW_{Min}, for example 2 and starts a timer. When the timer expires, it resets CW to CW_{Min}, to give transmission opportunities to other stations which may become active in the middle.

In other cases, the backoff timer of a station is interrupted by other's transmissions. We distinguish two situations, the stable state when the number of active stations does not change for some time, and the transient state during which the number of stations changes suddenly. This is illustrated in Fig. 3. In the stable state, the current number of active stations, N_1, does not vary over a relatively long period compared to the CW update interval, then $I(t)$ fluctuates around I_m with small differences. The role of the PD controller is to drive each CW around $CW^*_{N_1}$, the optimal CW value for the number of stations N_1. On the other hand, when there is a sudden change in the number of stations from N_1 to N_2, the observed error will be much larger. Our PD controller can resolve this disturbance quickly to establish a new stable state.

1) The Transducer Approximation: In section III-A, we have derived that

$$P_I = (1-\tau)^N, \quad and \quad P_S = N\tau(1-\tau)^{N-1}, \qquad (11)$$

where $\tau = \frac{1}{\frac{CW(t)}{2}+1}$. Therefore, P_S can be rewritten as

$$P_S = NP_I \frac{\tau}{1-\tau} = NP_I \frac{\frac{1}{\frac{CW(t)}{2}+1}}{1-\frac{1}{\frac{CW(t)}{2}+1}} = \frac{2NP_I}{CW(t)} \qquad (12)$$

Also, we have the following equations

$$P_I = \frac{I(t)}{I(t)+1}, \quad and\, P_B = 1 - P_I = \frac{1}{I(t)+1} \qquad (13)$$

Then the average busy duration T_B, can be computed as

$$\begin{aligned} T_B &= T_S \tfrac{P_S}{P_B} + T_C \tfrac{P_C}{P_B} \\ &\approx T_S \tfrac{P_S}{P_B} \quad (if\, T_S P_S \gg T_C P_C) \\ &= T_S \tfrac{2NP_I}{CW(t)P_B} \quad (by\,(12)) \\ &= \tfrac{2NT_S I(t)}{CW(t)} \quad (by\,(13)) \end{aligned} \qquad (14)$$

Or equivalently,

$$I(t) = \frac{T_B}{2NT_S} CW(t) = K_N \cdot CW(t) \qquad (15)$$

Therefore, $I(t)$ is approximately linear with $CW(t)$ for a certain N. Assume variations in K_N's (due to different N's) do not affect the controller's design much, therefore we use a proper K_0 to denote all K_N's. Now the remaining problem is how to select K_0. One simple approach is to make a rough estimation by using some typical values of the variables in (15). Another possible approach is to sample a set of input and output pairs while varying N, and use system identification methods to compute K_0 according to the specified accuracy. Generally, $0.005 < K_0 < 0.1$ (e.g., $K_0 = 0.0313$). Therefore, the transducer function in Fig. 2 is simply a scaling factor

$$H(s) = K_0 \qquad (16)$$

Then the system transfer function is formulated as

$$\begin{aligned} T(s) &= \tfrac{CW(s)}{I_m(s)} = \tfrac{G_c G_0}{1+G_c G_0 H} \\ &= \tfrac{\frac{K_p+K_d s}{s}}{1+\frac{K_p+K_d s}{s}K_0} = \tfrac{K_d s+K_p}{(1+K_0 K_d)s+K_0 K_p} \end{aligned} \qquad (17)$$

2) Steady State Error: In the ideal case, the steady state error should be zero, i.e., $\lim_{t\to\infty} e(t) = 0$, or equivalently, $\lim_{t\to\infty} I(t) = I_m$. Apply the Final Value Theorem to $\lim_{t\to\infty} I(t)$, we can get:

$$\begin{aligned} & \lim_{t\to\infty} I(t) = \lim_{s\to 0} sI(s) \\ = \; & \lim_{s\to 0} sH(s)W(s) = \lim_{s\to 0} sH(s)T(s)I_m(s) \\ = \; & \lim_{s\to 0} sH(s)T(s)\tfrac{I_m}{s} = \lim_{s\to 0} I_m H(s)T(s) \\ = \; & \lim_{s\to 0} I_m K_0 \tfrac{K_d s+K_p}{(1+K_0 K_d)s+K_0 K_p} = I_m \end{aligned} \qquad (18)$$

Therefore, the system transfer function satisfies the property of zero steady state error.

3) Tuning the Controller Gains: For system stability, the poles in $T(s)$ should have negative real part, i.e.,

$$-\frac{K_0 K_p}{1+K_0 K_d} < 0 \qquad (19)$$

Intuitively, if $e(t) > 0$ or $\dot{e}(t) > 0$, CW should be increased. Therefore, we have the following constraints:

$$K_0 > 0,\; K_p > 0,\; K_d > 0. \qquad (20)$$

Combining (16), (19) and (20), we can get various sets of solutions (e.g., one of the possible solutions is given by $K_0 =$

0.0313, $K_p = 35$, $K_d = 3$). Now we can derive $CW(s) = G(s)E(s)$ using the solutions for $(K_0,\, K_p,\, K_d)$, where:

$$G(s) = \frac{CW(s)}{E(s)} = \frac{K_d s + K_p}{s} \tag{21}$$

We have mentioned that one of our design requirements is to make ΔCW upper-bounded by ΔCW_m. This is reflected in $(K_p,\, K_d)$, which should not be too large so that CW will not change too much in one step.

4) CW Control Rule: The analysis above is based on a continuous model. However, when implemented in a real plant, (21) must be discretized. By some standard transformation method (e.g., tustin), the discrete control rule is:

$$G(t) = \frac{C_1 t + C_0}{t - 1} \tag{22}$$

where (C_1, C_2) is dependent on $(K_p,\, K_d)$ and the transformation method. (22) is equivalent to:

$$CW(t) = CW(t-1) + C_1 e(t) + C_2 e(t-1) \tag{23}$$

Obviously, (23) can be easily implemented in the control block of a plant. The formal description of our proposed CW Idle-Slots-based Control is illustrated in Algorithm 1.

Algorithm 1 Contention Window Control

```
$CW$ Idle-Slots-based Control.
while Backoff before sending a packet do
    if $backoff\ timer\ is\ paused\ or\ expires$ then
        $I_{avg} = \alpha I_{avg} + (1 - \alpha) I_{cur}$;
        $e_{prev} = e_{cur}$;
        $e_{cur} = I_m - I_{avg}$;
    end if
    if $timer\ is\ not\ paused\ for\ H \geq H_1\ transmissions$ then
        $CW_{cur} = CW_1$;
    else if $timer\ is\ not\ paused\ for\ H < H_1\ transmissions$ then
        $CW_{cur} = CW_{Min}$;
    else
        $CW_{cur} = CW_{cur} + C_1 e_{cur} + C_0 e_{prev}$;
    end if
end while
```

5) Discussions: Our throughput analysis presented above is based on the assumption that each station operates at perfect channel conditions. However, in practice, the wireless channel is time varying and bit rates are inhomogeneous among geographically distributed stations using rate adaptation techniques. With a throughput-fair MAC, rate diversity leads to "performance anomaly" [19]. Time-based fairness is proposed to eliminate this phenomena, which can be achieved by scaling the access probability of different hosts. With respect to our scheme, it means that each host scales the $CW(t)$ computed using (23) by a factor of $\frac{r_{max}}{r_{cur}}$, the ratio between the maximum bit rate r_{max} and its current bit rate r_{cur}. We also note that our scheme can be extended to satisfy other fairness requirements (e.g., flow-based / weighted / proportional fairness).

IV. PERFORMANCE EVALUATION

In this section, we compare the performance of the proposed CW control algorithm with the standard BEB using $NS2$ [20]. TABLE I lists the MAC/PHY and control parameters used in the simulation. CBR traffic is used to study the saturation behavior of both algorithms. We run each experiment for at least 100 secs with MAC data payload size 1000 Bytes. In section IV-A, throughput and fairness performance are evaluated under different contention levels. To study the responsiveness of the proposed control algorithm, in section IV-B, we measure the CW dynamics when varying the number of active stations.

TABLE I

MAC/PHY AND CONTROL PARAMETERS USED IN SIMULATION

CW_{Min}	31	BasicRate	1 Mbps
CW_{Max}	1023	DataRate	11 Mbps
CW_1	2	RTSThreshold	3000
SlotTime	20 μs	I_m	5.0
SIFSTime	10 μs	K_0	0.0313
DIFSTime	50 μs	(K_P, K_d)	(35, 3)
PHY Overhead	192 μs	(C_1, C_0)	(11.75, 5.750)

A. Throughput vs. Fairness

As shown in Fig. 4, WISC achieves more stable throughput performance, while that of BEB degrades a lot as the number of contending stations increases. In terms of fairness, we compute Jain Fairness Index by (24). Our approach also yields much better fairness than BEB, regardless of the network configuration (Fig. 5). In both cases, when the number of active stations is larger, the improvement is more significant (more than 30% in terms of throughput). The poor performance of BEB is due to the increase of collisions when the network size increases, which is collision-triggered and resets CW after each success. On the other hand, WISC observes the channel state distributively and automatically updates CW around the optimal value to maintain a low collision ratio. Therefore, it can closely approach the theoretical limit, even when the number of active stations is large.

$$f(x_1, x_2, ..., x_N) = \frac{(\sum_{i=1}^{N} x_i)^2}{N \sum_{i=1}^{N} x_i^2} \tag{24}$$

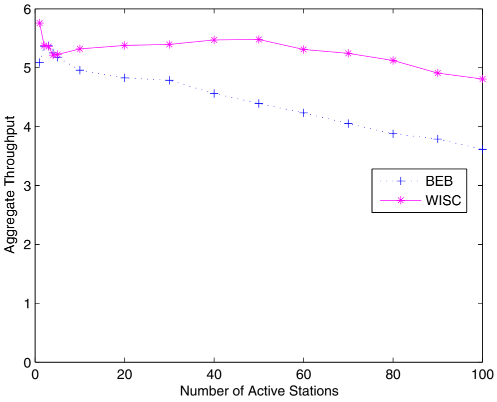

Fig. 4. Aggregate throughput vs. number of active stations.

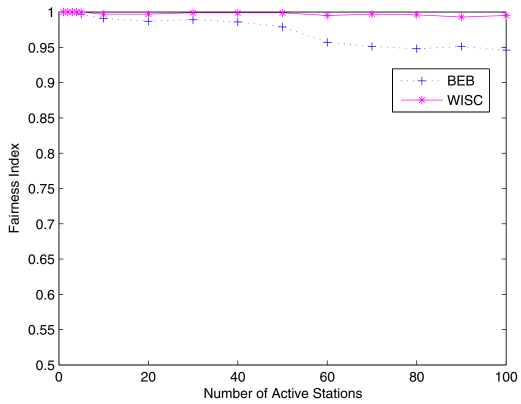

Fig. 5. Fairness index vs. number of active stations.

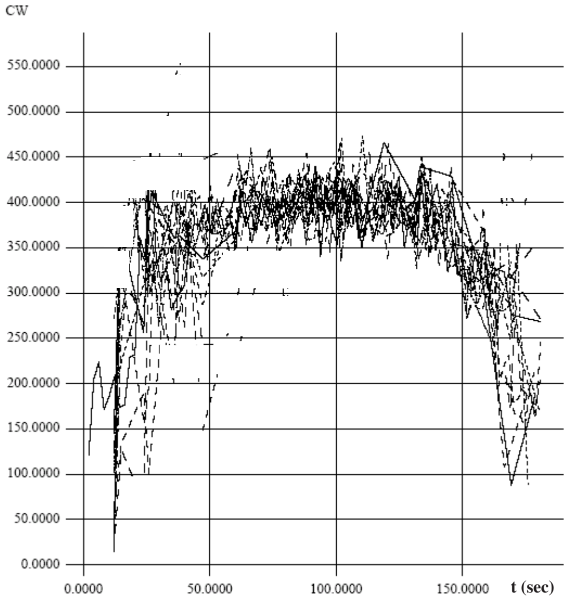

Fig. 6. Dynamics of CW when varying the number of active stations.

B. *Dynamics of CW*

In a WLAN system, stations may become on and off randomly, which makes the number of active stations highly dynamic. To keep the channel utilization high as well as avoid delay/jitter, the proposed CW control algorithm must react fast to the varying contention levels. We simulate a scenario where the number of active stations, N, gradually goes up ($N = 5, 10, ..., 50$) in the first 100 secs, and then goes down ($N = 50, 45, ..., 5$) in the next 100 secs. The sampled CW dynamics is illustrated in Fig. 6. Obviously, these measurements closely follow the theoretic optimal values while being responsive, which demonstrates the effectiveness of the proposed scheme.

V. CONCLUSION

In this paper, we propose CW Idle-Slots-based Control (WISC), from a control-theoretic approach, which can achieve stability, convergence and responsiveness. The basic idea of WISC is to adjust CW based on a locally available channel state, by using a well-designed smart controller, so that it automatically converges to the optimal value. Simulation results under saturation traffic demonstrate that our scheme outperforms the standard BEB in terms of both throughput and fairness. It is simple, efficient and readily to be implemented in real 802.11 products since no hardware change is required. Also, it can be easily extended to operate under various network configurations and satisfy different QoS requirements.

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