AP-based CW Synchronization Scheme in IEEE 802.11 WLANs

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Abstract— **In this paper, an optimal contention window (CW) synchronization scheme is proposed in IEEE 802.11 WLANs. IEEE 802.11 WLANs operates with Distributed Coordination Function (DCF) mode for the Medium Access Control (MAC). In DCF, CW becomes the minimum CW according to the success of data transmissions and increases exponentially due to the collisions. In this situation, the smaller value of the minimum CW can increase the collision probability because stations have higher opportunity to access the medium. On the other hand, the higher value of the minimum CW will delay the transmission, which can result in the network performance degradation. In IEEE 802.11, since the base minimum CW value is a fixed value depending on the hardware or standard, it is difficult to provide the optimal network performance that can be determined by the flexible CW value with respect to the number of active stations. In addition, the synchronization of optimal CW is required among mobile stations to adapt the network parameters. Especially for the newly joined stations such as moving or turning on stations, they need to adapt the minimum CW value to get the optimal network performance. The shorter the adaptation time is, the better the network performance can maintain. Therefore, in this paper, the access point (AP) calculates the optimal CW and shares it with mobile stations using beacon and probe response messages for the fast CW synchronization. From the extensive simulation results, the proposed scheme has better performance compared to the previous schemes in terms of the network throughput and adaptation time.**

Keywords— **WLAN; Optimal CW; CW Synchronization.**

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I. Introduction

Wireless local area networks (WLANs) based IEEE 802.11 have become the most popular and widely distributed networks worldwide due to the rapid deployment, low cost, and easy configuration. Based on the Cisco report, the wireless traffic from 2016 to 2021 has been increased about a 47% compound annual growth rate (CAGR) in the world. In this situation, the data traffic through WLANs increases from 42% in 2015 to 49% in 2021 [1, 2]. Currently, WLANs have become a universal solution for an ever increasing wireless application fields. WLANs according to the IEEE 802.11 standards have showed rapid growth over the years. Especially, as the spread of Internet of Things (IoT) and smartphones has become more common, WLANs have been attracted much attention [3-5].

The medium access control (MAC) of IEEE 802.11 offers Distributed Coordination Function (DCF) and Point Coordination Function (PCF) [6]. PCF, which aims to provide a service without contentions, is a centralized MAC protocol that coordinates stations through the access point (AP) based on the polling procedures. On the other hand, DCF is a contention-based approach that utilizes Carrier Sensing Multiple Access / Collision Avoidance (CSMA/CA) mechanisms with binary exponential backoff algorithms. Among them, DCF is a basic MAC protocol adopted in IEEE 802.11 to allow the random access for the wireless mediums while PCF is optional. In DCF, if the station wants to deliver the data, it is necessary to listen to the status of the channel during the Distributed Inter-frame Space (DIFS) time. DIFS time is the amount of time that a station should wait since the last use of the wireless medium when each station tries to access the wireless medium in DCF. If the other stations are using the channel during the DIFS time, the station must wait for the access to the channel until the other stations finish transmission through the channel. If the channel is not busy during the DIFS time, the station selects a random backoff value, which is randomly selected from the contention window (CW) within [0, CW] where the initial CW value is the minimum contention window (CW_{min}). Then, actual waiting time is calculated with the multiplication by the slot time (T_{slot}). Whenever the station successfully transmit the data, the CW is initialized to CW_{min}. On the other hand, if two or more stations try to transmit the data simultaneously,

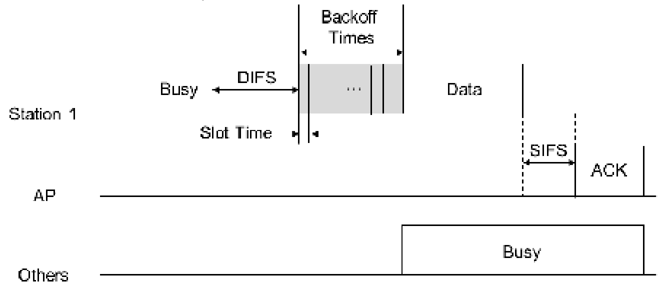

Fig. 1 Basic DCF operation

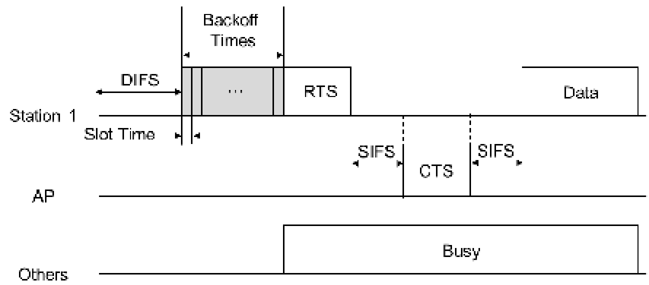

Fig. 2 RTS/CTS operation

which means that the collision occurs, *CW* doubles until the value reaches the maximum contention window value (CW_{max}).

The value of CW_{min} affects the network performance because each station always has to wait for the access to the channel for the backoff time proportional to CW_{min} [7, 8]. For example, smaller CW_{min} will be appropriate for the network where small number of stations exist because there can be relatively low collision probability. However, for the dense environment, larger CW_{min} will be more suitable to reduce the collision.

IEEE 802.11 currently works by setting a fixed static value of CW_{min} according to hardware chipsets and standards. This results in the network performance degradation due to the use of non-flexible CW values which can only be changed according to the last transmission status (i.e., success and failure) [9, 10]. To solve this issue, many researches have been conducted to find an optimal *CW* which can increase the network throughput and reduce the collision probabilities [7-15]. However, these studies did not consider how to synchronize optimal *CW* value with other stations in the network or incoming stations into the network. This means that newly joined stations need adaptation time to get the optimal *CW* by means of its own way.

Therefore, this paper proposes a method to synchronize the optimal *CW* values with other stations within the network, so that all stations can use the optimal *CW* values without long adaptation time to ensure optimal network performance.

II. The Material and Method

In this chapter after reviewing the related works including basic DCF operation, scanning procedures, and studies on existing *CW* adjustment, the proposed scheme will be described.

A. Related Works

1) Basic DCF Operation: As briefly described above, IEEE 802.11 WLANs use DCF as the default medium access

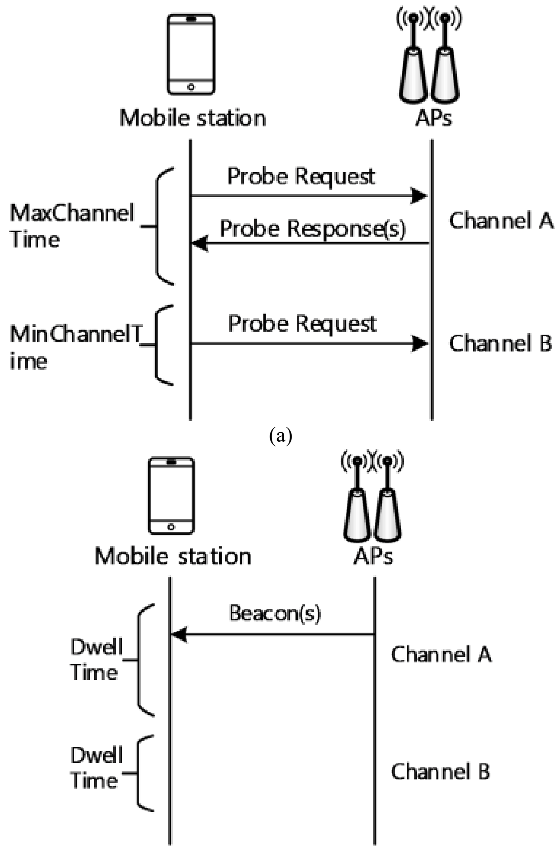

Fig. 3 Scanning procedures: (a) active scanning, (b) passive scanning

control method that is based on CSMA/CA. In Fig. 1, Station 1 wants to send data to AP based on DCF operation. In the DCF method, the mobile stations sense the medium to check whether medium is busy or not. If Station 1 senses that the medium is not busy for a DIFS period, it starts to perform the random backoff procedure. In this procedure, backoff timer is set as the random backoff times using the specific backoff value multiplied by T_{slot}, where the backoff value is a random integer value from the uniform distribution within the values [0, *CW*] and T_{slot} is determined by the physical layer characteristic. *CW* value has the minimum value of CW_{min} and maximum value of CW_{max}. If the channel is not busy during DIFS, the station creates a random backoff time within [0, *CW*] and starts to reduce the backoff counter. When the backoff counter value becomes zero, Station 1 transfers the data at the beginning of the slot to AP. When the data is successfully transmitted, AP sends an ACK message after SIFS time. Then *CW* is always re-initialized to CW_{min}. However, if the packet is not delivered successfully, the range to determine the backoff time will be changed from [0, *CW*] to [0, 2x*CW*]. This means that the current backoff timer range is doubled for each transmission failure up to its maximum. When *CW* becomes the maximum value, *CW* is not changed although the collision occurs again. Meanwhile, if other stations detect that the channel is not idle because of the communication between Station 1 and AP, the backoff timer of them stops decreasing until the channel is idle again. Optionally, as shown in Fig. 2, exchange of request to send (RTS) and clear to send (CTS) can be utilized before the actual data delivery to lower the collision probability. In RTS/CTS mode, Station 1 that wants to transmit data also should wait until the medium is not busy after DIFS. When the backoff timer becomes zero, Station 1 sends a RTS instead of data to reserve the medium. Then, AP sends CTS after SIFS period which is shorter than DIFS. In addition, network allocation vector (NAV) which is for other stations to use virtual carrier sensing, is also included in RTS and CTS. Then, other stations receiving NAV set their timer and defer the medium access until NAV expires [16]. This method is the virtual carrier sensing. However, for both the current basic DCF and RTS/CTS operations, the network throughput performance cannot be optimized at its best because it uses a fixed CW_{min} value without considering the number of stations and the network state [7-9].

2) Scanning procedure: In 802.11 WLANs, each station tries to discover nearby APs for connection. In order to find the suitable AP, the station should perform scanning procedure. As shown in Fig. 3, there are two scanning procedures: active and passive. Fig. 3(a) describes the active scanning procedure. During the active scanning procedure, the station transmits a probe request which is a broadcasting message and waits for the probe response in response to the probe request from an AP. The station transmits the probe request via each channel. If there are multiple APs operating in the same channel (channel A in Fig. 3(a)), the station can receive the multiple probe responses from multiple APs. In this case, since there can be more than one APs, the station waits for the probe response in the channel during MaxChannelTime. However, if there is no response in the channel during MinChannelTime such as channel B in Fig. 3(a), the station moves to the next channel and again sends the probe request message repetitively. On the other hand, in the passive scanning procedure as shown in Fig. 3(b), the station waits for the beacon messages at each channel sent periodically by each AP. The dwell time to wait for the beacon messages at each channel can be various. For example, the station can wait for the beacon message only one beacon interval (e.g., 100ms) or more than one beacon interval to expect more than one beacon messages from other APs as shown in Fig. 3(b). Since stations wait for the beacon message passively, the passive scanning procedure will take more time generally than that of the active scanning procedure. Based on the both scanning procedures, stations can recognize the list of nearby APs and try to connect with one appropriate AP among them [17, 18].

3) *Studies on Existing CW Adjustment*: So far, there have been conducted to calculate the optimal *CW* to increase throughput and reduce the collision probability. Two types of *CW* adjustment are classified: fixed *CW* and adaptive *CW* adjustment mechanisms. Different from the basic method which converts the existing *CW* value to the initial *CW* value (CW_{min}) after successful transmission to increase throughput and reduce the collision probability, various methods of slowly decreasing the value have been proposed for fixed *CW* mechanism [7-9]. For example, the exponential increase/decrease algorithm divides the existing *CW* value in half rather than changing the *CW* value to the initial *CW* value (CW_{min}) when the data transfer is successful. However, changing the *CW* value at a fixed rate of the EIED algorithm makes it difficult to determine the optimal *CW* value based on the network state. Therefore, the EILD (exponential increase linear decrease) algorithm was proposed to solve this problem

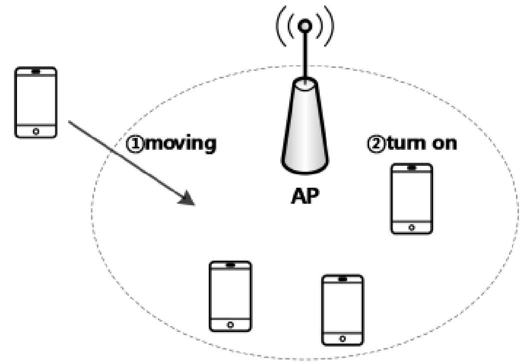

Fig. 4 Two scenarios where *CW* synchronization is required

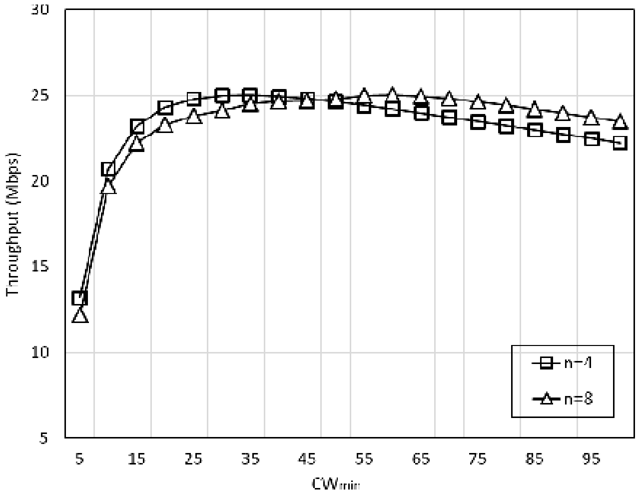

Fig. 5 Throughput according to CW_{min}

[8-10]. It makes linear reduction of *CW* value function when data transmission is successful. In addition, several other algorithms have been introduced including the multiple increase/decrease and efficient exponential threshold algorithms [11-13]. Theses algorithms have improved network performance by means of various incremental metrics to determine the size of *CW*. However, these are difficult to handle the changes in the network conditions. Since the *CW* adjustment is decided by the last transfer attempt, it reduces throughput with increasing number of stations. On the other hand, the adaptive *CW* mechanism has been provided dynamically considering the current network status such as the number of active stations or network traffic loads [7, 9, 14-15]. While these methods allow us to establish optimal *CW* for each network condition, there is a lack of consideration on how to share optimal *CW* values with all stations in the network. For example, as shown in Fig. 4, there can be two scenarios where *CW* synchronization is required. First scenario is that a mobile station moves into the coverage of AP. Since the station tries to connect to AP with its own initialized *CW* which is configured with a fixed value defined in the hardware chipset or standard, it is not same with the current optimal *CW* of the network. Similarly, for a mobile station which is turned on in the network, it also operates with its own initialized *CW*. Since these stations

need time to adapt to find the optimal *CW* by its own way, overall network performance can be degraded.

B. Proposed Scheme

In this paper, we intent to use the optimal *CW* values mathematically demonstrated in DCF [7, 9]. The optimal *CW* estimation method uses the channel state information to calculate the number of active stations, and considers network loads according to the algorithms. The optimal *CW* values [7] are calculated as shown in (1).

$$CW^* = (\frac{CW_{\min}}{2}) \times n - 1 \tag{1}$$

Where CW^*, CW_{min}, and n are the optimal *CW* value, minimum *CW* value, and the number of active stations, respectively. The expected number of active stations can be obtained using channel state information [7].

For example, by means of simulation, Fig. 5 shows the network throughput performance according to CW_{min} when the number of stations is four and eight. It can be noted that the network throughput is dependent on CW_{min} and the optimal value of CW_{min} should be determined considering the number of stations.

In this paper, we propose a method to share the optimal *CW* value obtained above with all stations within the network. The optimal CW value should be synchronized with all existing connected stations as well as stations that want to be newly accessed due to movement and turning on events, so we want to mount it on beacon and probe response to share the *CW* values through as various paths as possible. Information sharing using beacon and probe response messages have been considered as an efficient method [19].

1) *Beacon*: As mentioned above, the beacon message is periodically sent by AP and utilized by the stations for the passive scanning procedure. The beacon message can include the optimal CW value calculated by the AP for all nearby stations. Since IEEE 802.11 standard does not have a field to include the value, the optimal CW value can be delivered through the Vendor Specific field [6]. Although the BSS Load field exist, it is not appropriate to include the CW value in this field because it is to provide the channel utilization such that the unassociated stations can choose the proper AP. Beacon messages are typically transmitted at 100ms intervals. This interval can be changed and is informed using the beacon interval field in the management frame body. If interval is set to 100ms, the optimal CW value is shared with the stations in the network within about 50ms on average. Since newly connected or turned on stations can also listen to beacon messages and attempt to connect to AP after passive scanning operation, they can recognize the optimal *CW* value and start to communicate with each other based on the received optimal *CW* value.

2) *Probe Response*: As mentioned above, the probe response message is a response from AP triggered by the probe request from the stations and utilized for the active scanning procedure. Since the frame body of the probe response is almost similar with that of the beacon message, the optimal *CW* value can be included in the Vendor Specific field of the probe response. This allows the stations which are in the active scanning procedure to recognize the optimal *CW* values and attempt to access the network based on the received optimal CW value.

After the station receives the optimal CW value, it directly can operate based on the value without any delay for the self-optimization to find the value.

From [20], the average length of a slot time (E_s) and average number of slot times (E_N) which is needed to transmit the data successfully can be calculated as

$$E_S = (1-p_{tr})T_{slot} + p_{tr}p_sT_s + p_{tr}(1-p_s)T_c \tag{2}$$

$$E_N = \frac{(1-2p)(CW_{min}+1) + pCW_{min}(1-(2p)^m)}{2(1-2p)(1-p)} \tag{3}$$

where p is the probability that there is a collision for the transmitted data and m is the maximum back-off stage. In addition, p_{tr} is the probability that there is at least one transmission in the slot time, p_s is the probability to complete the transmission successfully, T_s is the average time that the medium is busy for each station during one successful data delivery, and T_c is the average time that the channel is not idle for each station during one collision. Then, if data size is fixed, T_s and T_c for the basic DCF operation can be obtained as follows [20].

$$T_s = H + P + SIFS + T_{slot} + ACK + DIFS + T_{slot} \tag{4}$$

$$T_c = H + P + DIFS + T_{slot} \tag{5}$$

where H means the transmission time of MAC and physical headers and P is the data transmission time.

Consequently, based on the beacon or probe response messages, the expected adaptation time (T_a) for the station to recognize the optimal CW value can be obtained by

$$T_a = E_N E_S \text{ (by probe response) or } I/2 \text{ (by beacon)} \tag{6}$$

where I is the interval time of beacon messages. Although the beacon can be delayed due to the transmissions from other stations, this paper assumes that the interval is almost same based on the control of AP.

TABLE I
SIMULATION PARAMETERS

Parameters	Values	Unit
Data size	8184	bytes
MAC header size	272	bytes
PHY header size	128	bytes
DIFS	28	µs
SIFS	10	µs
Slot time	9	µs
Propagation delay	1	µs
Beacon interval	100	ms
Data rate	54	Mbps

III. RESULT AND DISCUSSION

For the validation of the analytic models, we developed an event-driven simulator based on MATLAB 2018a and carried out extensive simulations. In order to evaluate the performance, network throughput and adaptation time are compared among the basic, proposed, Idle-Sense [14] schemes. In Idle-Sense, each station by itself estimates the average number of idle slots between the attempts of the

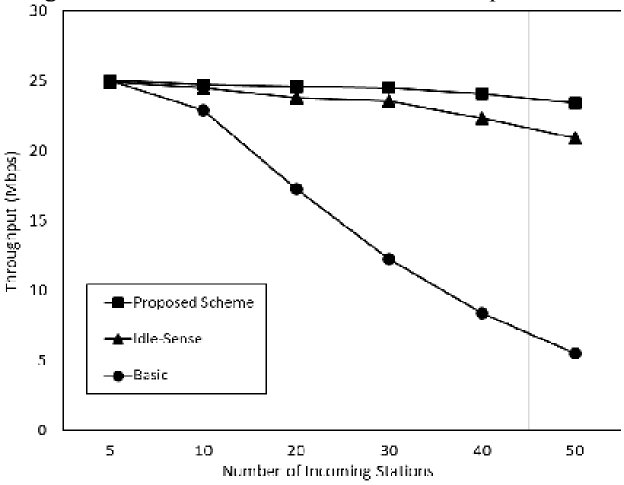

Fig. 6 Throughput according to the number of stations

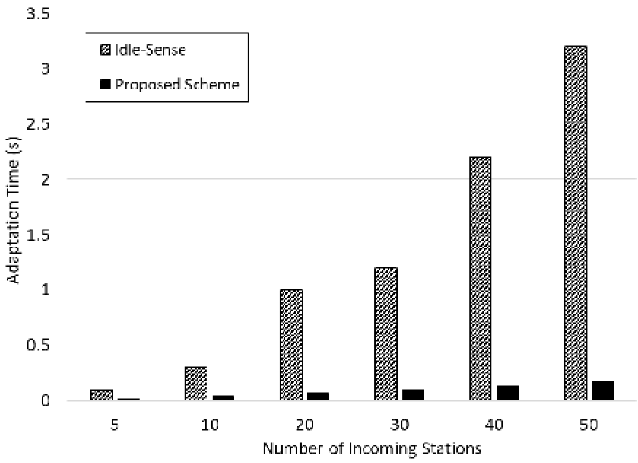

Fig. 7 Adaptation time according to the number of incoming stations

delivery. Simulation parameters are based on Table 1. In addition, this paper utilizes the fluid-flow model that stations travel with a constant speed and in one direction for the sake of simplicity. We assume a network scenario where the number of nodes with initial parameter move into the network including the existing three stations in the network.

Fig. 6 shows the throughput according to the number of incoming stations. Based on the fluid-flow model, stations move into the network one by one with 5 seconds intervals. Since the basic scheme uses the static CW_{min} value, the optimal CW is not utilized at each situation. This results in the network throughput degradation as the number of incoming stations increases. On the other hand, since both Idle-Sense and the proposed scheme adapts the CW value according to the number of nearby stations, they have higher network throughput compared to that of the basic scheme. It can be noted that the gap between the proposed scheme and Idle-Sense becomes higher according to the incoming number of stations. This is because the unsynchronized period (i.e., adaptation time) for each station becomes longer in Idle-Sense than that in the proposed scheme. In other words, since Idle-Sense calculate the optimal CW at each station when it moves into the network coverage considering other nodes, the performance degradation can be higher when there are more hidden nodes from the incoming node's perspective.

Fig. 7 shows the adaptation time according to the number of incoming stations. Adaptation time is defined as a period

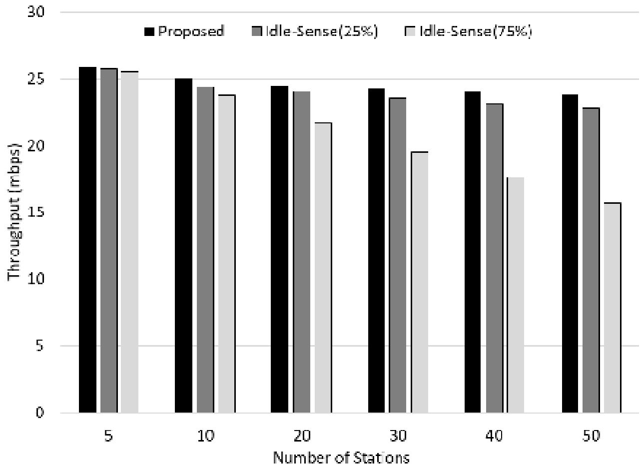

Fig. 8 Throughput according to the number of stations with a% of new incoming users

that the network achieves a throughput larger than 95% of the maximum value it can have [15]. Idle-Sense has higher adaptation time since it can calculate the optimal CW at each station whenever the station moves into the network considering other stations. Specifically, the station by itself should estimate the average number of idle slots between the attempts of the transmissions to find the optimal CW, which can take long adaptation time especially with lots of new stations. On the other hand, the adaptation time of the proposed scheme can be calculated as the time until the successful transmission of probe response or beacon message from AP to stations. This is because whenever the station moves to the network, the optimal CW is calculated in the AP side centrally then shared through the beacon and probe response messages with all existing stations. If the number of nodes increase continuously, the period can be close to the beacon interval. In the field, since the beacon can also be delayed by the data transmissions of other stations, the adaptation time of the proposed scheme can be slightly increased due to this delay.

Fig. 8 shows the throughput according to the number of stations with a% of new users. For example, 25% new users means that 25% of the total number of stations newly join the network at the same time. Since new users have their own initial CW_{min} value, they operate using the value when they join the network. For Idle-Sense scheme, higher percent means that higher adaptation time is required. As explained above, this is because the stations in Idle-Sense should estimate by itself the average number of idle slots between the transmission tries. Thus, if lots of new stations appear simultaneously, estimation becomes more difficult because those new stations try to estimate initially with their own CW_{min}. On the other hand, in the case of the proposed scheme, since percent does not affect to the performance, differentiation is not included. This is because the AP centrally calculates when the stations connect to it and shares the optimal *CW* within short adaptation time thanks to the beacon or probe response messages.

IV. Conclusion

In this paper, an optimal *CW* synchronization scheme in IEEE 802.11 WLANs is proposed. Since previous researches just focused on finding optimal *CW* value without consideration on how to synchronize the value with stations, each station should try to find the value based on its own network view, which results in network performance degradation. Furthermore, the performance degradation becomes severe according to the increasing number of newly joined stations due to the movement and turning on events. Therefore, this paper proposes a simple *CW* synchronization scheme by means of beacon and probe response messages. In addition, performance evaluation results show that the proposed scheme can have higher network throughput and reduced adaptation time compared with previous researches. In our future work, the experiments with smart phones and AP will be conducted considering real environments.

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