An OFDMA based Concurrent Multiuser MAC for Upcoming IEEE 802.11ax

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***Abstract*—Recently, IEEE drew up a new task group named TGax to draft out the standard IEEE 802.11ax for next generation WLANs. However, the average throughput is very low due to the current medium access control (MAC) protocol. A promising solution for this problem is to draw Orthogonal Frequency Division Multiple Access (OFDMA) into IEEE 802.11ax to enable multiuser access. The key challenges of adopting OFDMA are synchronization and overhead reduction. In this paper, we propose an OFDMA based Multiple Access for IEEE 802.11ax (OMAX) protocol to solve both two challenges above. The whole channel physical channel sensing and fast backoff are adopted to ensure synchronization, while enhanced RTS/CTS mechanism and new frame structure are designed to reduce overhead. Moreover, the mathematic model of OMAX is formulated, and the performance of OMAX is analyzed. The analysis and simulation result indicate that the proposed OMAX protocol increases the throughput to 160%.**

Keywords*—*Next Generation WLANs; IEEE 802.11ax; MAC; OFDMA

I. INTRODUCTION

Wireless local area networks (WLANs) based on IEEE 802.11 protocol have been ubiquitous in our life to provide high speed wireless connectivity at home, offices, and public places. In 1999 the peak physical rate of 802.11b is 11Mbps with direct sequence spread spectrum (DSSS) technology, while in IEEE 802.11a/g the peak physical rate is 54Mbps with Orthogonal Frequency Division Multiplexing (OFDM) technology [1]. In 2009, based on 40MHz bandwidth and 4X4 MIMO, the peak physical rate of IEEE 802.11n is 600Mbps [1]. In 2013, IEEE 802.11ac improved the peak rate of IEEE 802.11n to 6.9Gbps by using 160MHz channel bandwidth and 8X8 MIMO [2]. After the proposal of IEEE 802.11ac, IEEE aimed to conceiving the next generation WLANs protocol. In March 2013 the study group for next generation WLANs named high efficiency WLAN (HEW) is established, and in May 2014 the task group TGac is set up [3].

In the functional requirements of IEEE 802.11ax, it is said that IEEE 802.11 should achieving at least four times improvement in the average throughput per STA, and should support dense deployment environment [4]. With the arising of more available bandwidth resource and new technology like MIMO, the physical rate in WLAN has been significantly improved. On the other hand, the MAC layer of WLANs barely changed for the past 15 years. WLANs adopted distributed coordination function (DCF) as the medium access control (MAC) layer protocol since its birth. In DCF protocol, any station (STA) can send data to access point (AP) at any time, and at the same time only one STA could use the channel resource and transmit data [1]. However, DCF used in IEEE 802.11 is more applicable to low density WLAN deployment, while in high density deployment cases the MAC efficiency of DCF would be very low due to the single user access and single user transmission [5]. Obviously, multiuser MAC is need to solve the problem above [6]. Reasonably, OFDMA technology in next generation WLANs is considered [7] since WLANs have already employed (OFDM) as their physical technology.

By deploying OFDMA, the subcarriers of all the bandwidth in WLANs is divided into some sub-channels, and each of them consists one subcarrier or multiple subcarriers depending on the protocol design requirement. Thus, it is possible that STAs could simultaneously access channel and transmit data to AP with OFDMA technology. Nevertheless, there are still two challenges for implementing OFDMA in next generation WLANs, synchronization and overhead reduction. Synchronization is one of the most important issues in OFDMA technology, since OFDM system is sensitive to synchronization error [8]. AP would successfully receive multiple packet from multiple STAs only if these STAs are in synchronization condition. Moreover, to guarantee multiple STAs simultaneously accessing channel and transmitting data, additional signaling is needed. However, too much signaling overhead significantly degrades system performance, thus overhead reduction should not be ignored.

Ever-increasing researchers focus on using OFDMA technology in WLANs. There are some works on adding OFDMA into DCF. [9] and [10] designed a protocol to enable the stations to contend for channel access both in time and frequency domain through a two-dimensional backoff scheme. In [9, 10] the synchronization issue is not considered, and it is difficult for this protocol coexist with legacy WLANs. [11] and [12] divide STAs into multiple groups, and the STAs in the same group share the same sub-channel for channel access. Once AP receives RTS from the sub-channels, it replies CTS to allocate the channel resource. Unfortunately, synchronization is still not considered in [11] and [12]. [13] and [14] use the legacy RTS to access channel for multiple time, and once AP has received enough RTS, it sends CTS to schedule the channel resources. [13] and [14] spend too much

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time to complete multiple STAs access, thus the signaling overhead would degrade the protocol performance.

To design a promising MAC protocol for next generation WLANs, the synchronization issue, and overhead reduction should be considered thoughtfully and carefully. The framework of an OFDMA based multiuser access for IEEE 802.11ax (OMAX) protocol is proposed for next generation WLANs in this paper. In OMAX protocol, whole channel physical channel sensing and fast backoff process are adopted to solve synchronization problem, while enhanced RTS/CTS mechanism and new frame structure are designed to reduce overhead. Moreover, the protocol performance of both average access number and saturation throughput is analyzed using mathematic model, and the analysis result is evaluated by simulation result.

The main contribution of this paper is as follow:

- A framework of OFDMA based MAC protocol is designed for next generation WLANs, including physical channel sensing, fast backoff process, enhanced RTS/CTS mechanism, and frame structures.
- The whole channel physical channel sensing and fast backoff are jointly adopted to solve synchronization problem. And the enhanced RTS/CTS mechanism and new frame structure are designed to reduce overhead.
- The mathematic model for the proposed protocol is formulated, and the protocol performance of both average access number and saturation throughput is analyzed. The simulation result shows that the proposed protocol increases the throughput to 160%.

The rest of the paper is organized as follows. The new MAC protocol based on OFDMA is proposed in Section II. The performance of the protocol in saturation scenario is analyzed in Section III. Performance evaluation is presented in Section IV to validate the new MAC protocol. The paper is concluded in Section V.

II. PROTOCOL DESIGN

In order to develop a high efficient random access protocol that can be used in the next generation WLANs, an new MAC protocol named OMAX is proposed in this section. The main idea of OMAX is that adopting physical channel sensing on whole channel and fast backoff process to guarantee synchronization among different STAs, and using enhanced RTS/CTS mechanism and frame structure to reduce overhead.

The procedure of OMAX is illustrated in Fig. 1:

1) STAs detect the whole channel according to the physical carrier sensing in DCF until the channel is idle for distributed inter-frame space (DIFS);

2) STAs carry out the back off process using the same backoff rules as in IEEE 802.11 DCF expect the backoff counter in STAs minus 4 for each idle slot since there are four sub-channels in Fig. 1;

3) After completing backoff, STAs randomly select one sub-channel to transmit request to send (RTS), and AP transmit group clear to send (G-CTS) to indicate the sub-channels allocation information according to the services requirement of different STAs;

4) STAs transmit DATA according to the information in G-CTS, and AP replies the group acknowledgement (G-ACK). The detail of OMAX protocol is described as follow.

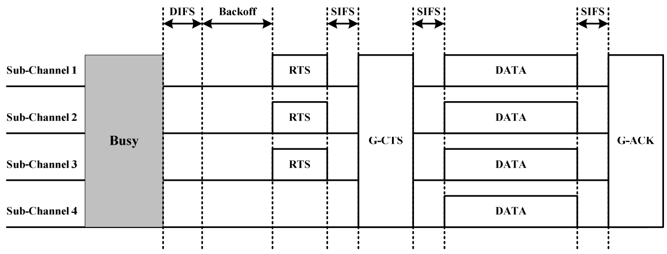

Fig. 1. The procedure of the proposed OMAX protocol.

A. Whole Channel Physical Channel Sensing

In inherent DCF protocol, STAs could not transmit packet when a STA has already started its transmission. Therefore, concurrent transmission occurs only when multiple STAs start their transmission simultaneously on different sub-channels. The signal detection performance is not degraded if the time mismatch is smaller than the cyclic prefix (CP) time of OFDM symbol [15]. It is very difficult for multiple STAs to start their transmission in CP time when sub-channel physical channel sensing is used. In other word, by using sub-channel physical channel sensing, STAs could start transmission randomly no matter whether they start transmission in CP time with other STAs. To overcome this drawback of sub-channel physical channel sensing, the whole channel physical channel sensing is used in OMAX. All STAs in WLAN sense the whole channel rather than sub-channels. If all the sub-channels in WLAN are in idle state the channel state is considered as idle, otherwise the channel state is considered as busy. Thus, once at least one STA starts transmission, the other STAs consider the channel state as busy. And those STAs whose backoff process complete in the same slot could simultaneously start transmission.

Another problem about synchronization is transmission delay among different STAs. The CP time is 0.8us in WLANs, and the typical WLAN coverage is smaller than 100m. Therefore, if the STAs start transmission in the same slot time and select different sub-channels, they are in synchronization condition.

B. Fast Backoff Process

In OMAX protocol, each node maintains only one backoff timer for all the sub-channels. The backoff counter is randomly chosen in the range of [0, CW], where CW is the contention window size. CW value is decided by the binary exponential backoff algorithm: CW is set to the minimum value at the first backoff stage for every transmission, and it is doubled after every failed transmission until the max value of CW is reached. A node transmit RTS after the backoff counter is zero.

Unlike IEEE 802.11 DCF, in OMAX protocol the backoff counter minus *N* for every idle slot, where *N* is the sub-channel number. For example, as shown in Fig. 2, there are total 4 STAs in network, and the channel is divided in 4 sub-channel. These four STAs choose a backoff counter independently, where the backoff counters are 15, 13, 20 and 23 respectively. After the channel is idle for DIFS period, each STA decreases the backoff counter by 4 per backoff slot as there are 4 sub-channels in network. STA 1 and STA 2 access channel after 3 slots since after 2 slots the backoff counter of STA 1 (remaining 3) and STA 2 (remaining 1) are both less than 4. At the same time, the remaining backoff counter of STA 3 is 8, and STA 4 is 11. Then STA 3 and STA 4 access channel after 2 slots since the backoff counter of STA 3 (remaining 0) and STA 4 (remaining 3) are both less than 4.

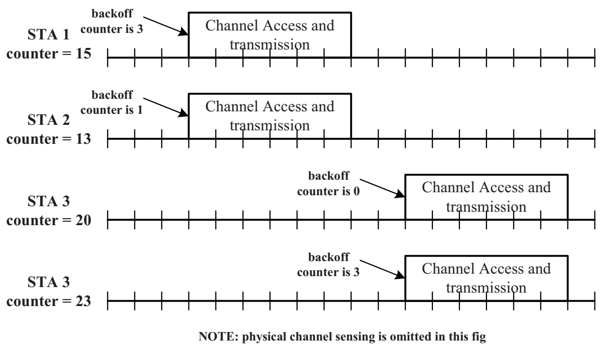

Fig. 2. The backoff process in OMAX protocol.

C. Enhanced RTS/CTS Mechanism

In traditional WLAN, if two STAs transmit RTS at the same time, the two RTS packets will collide with each other and AP can not receive either of them. However, in OMAX protocol, when several STAs transmit RTS simultaneously, AP is still receive some RTS packets as illustrated in Fig 3. Though (RTS 1, RTS 2) and (RTS 3, RTS 4) are collided in sub-channel 1 and sub-channel 2, RTS 5 in sub-channel 3, RTS 6 in sub-channel 4 and RTS 7 in sub-channel 5 are successfully received by AP. Overall, there are total 7 STAs transmitting RTS, and AP received 3 RTS in all.

Once AP receives RTS from each sub-channel, it will calculate the subcarrier assignment using some scheduling algorithm, which is out of the scope of this paper. In this subsection, we adopt a kind of round robin scheduling algorithm. For instance, the channel is divided into 4 sub-channel at first, and AP needs to allocate 4 sub-channels to the STAs successfully transmitting RTS. If there are 4 STAs successfully transmitting RTS, each STA obtain 1 sub-channel; if there are 3 STAs successfully transmitting RTS, one STA obtain 2 sub-channels while each of the other 2 STAs obtain 1 sub-channel, and so on. After the calculation, AP adds the scheduling result in G-CTS in OMAX protocol.

After receiving G-CTS from AP, STAs successfully completing RTS transmission wait short inter-frame space (SIFS) time in the first place, and then transmit DATA simultaneously through their assigned sub-channels. Finally, after AP receives the DATA packets from each sub-channel, it transmit G-ACK. ACK packet is defined in IEEE 802.11 protocol for acknowledging a MAC packet. But in OMAX protocol, AP need to acknowledge several MAC packet from different STAs. So G-ACK is used to imply that there are acknowledgement information for some STAs.

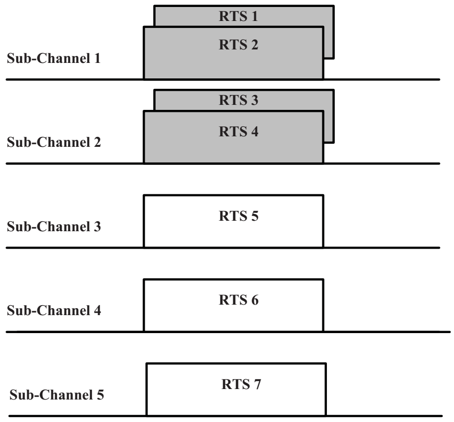

Fig. 3. RTS transmission in OMAX protocol.

D. New Frame Structure

In OMAX protocol, the new frame structure of RTS and DATA is as same as in DCF, and the only difference between RTS and DATA in OMAX and in DCF is that RTS and DATA in OMAX is transmitted in sub-channel rather than the whole channel.

However, the frame structures of G-CTS and G-ACK in OMAX protocol are different from the frame structure of G-CTS and G-ACK in DCF as shown in Fig. 4. There are more than one Revive Address (RA) field in G-CTS, and there is a scheduling information (SI) field follows each RA field to indicate the sub-channel allocation. There are total 16 bits in SI field to present allocation information of at most 16 sub-channels, in which 1 indicates the corresponding sub-channel is allocated to the STA, and 0 indicates the corresponding sub-channel is not allocated to the STA. For G-ACK frame, there is an additional ACK info field to acknowledge all the DATA packet AP has received. Since there are most 16 sub-channels in WLAN, ACK info field is also 16 bits as the same in SI field. Moreover, the receiver of G-ACK is a group of STAs, the RA field in G-ACK is the address of AP rather than any STA address.

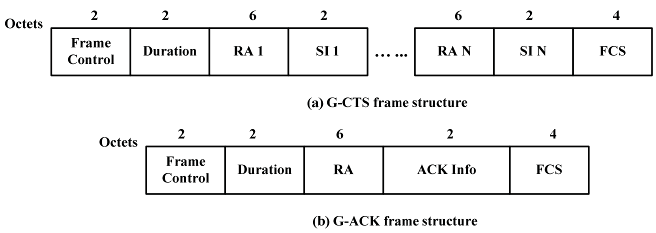

Fig. 4. G-CTS and G-ACK frame structures.

III. MATHEMATICAL ANALYSIS

In this section the saturation throughput of OMAX is analyzed using the analytical model in [16]. We assume that there is one Basic Service Set (BSS) consisting of n STAs with one AP located at its center, and there are total l sub-channels in BSS. Every STA always has packets available for transmission. In other words, this WLAN is under a saturated condition, where the transmission queue of each STA is always non-empty. An ideal channel condition is assumed, thus there is no packet errors caused by channel fading. Therefore, the packet errors only occur when there are more than one RTS in the same sub-channel, and do not occur in G-CTS, DATA and G-ACK transmission. The notation $W_i = 2^i W$ is adopted, where $i \in (0, m)$ is called a backoff stage, and $W = CW_{min}$ (the minimal contention window). Let m be the maximum backoff stage, thus $CW_{max} = 2^m W$ (the maximum contention window). For each failed RTS transmission, STA increase the backoff stage to current backoff stage plus one unless the maximum backoff stage is reached. The minimal backoff state is 0, and the corresponding contention window is W. The maximum backoff state is m, and the corresponding contention window is $2^m W$. It is assumed that a STA attempts to transmit RTS packet until successful.

A. Transmission Probability

Let τ be the probability that a STA transmits RTS in a randomly chosen time slot and a randomly chosen sub-channel, and p be the probability that the RTS transmitted by one STA collides with other RTS in the same sub-channel. The relationship between τ and p is shown in (1) and (2). By using numerical techniques, the nonlinear equations (1) and (2) can be solved [16].

$$p = 1 - (1-\tau)^{n-1}, \tag{1}$$

$$\tau = \frac{2(1-2p)}{(1-2p)(W+1) + pW(1-(2p)^m)}. \tag{2}$$

B. Mean Successful RTS Transmission Number

The successful RTS transmission on one sub-channel occurs when there is one STA transmitting RTS, and other $n-1$ STAs do not transmit RTS on a specific sub-channel. So the probability P_{sub} that there is only one STA transmitting RTS on one specific sub-channel is given by

$$P_{sub} = n\tau(1-\tau)^{n-1}. \tag{3}$$

However, several STAs could transmit RTS successfully in the same time slot on different sub-channel in OMAX. Thus, the probability $P_{suc}(i)$ that $i (i \in [1, l])$ STAs transmit RTS successfully in density deployment is approximately given by

$$P_{suc}(i) = \binom{l}{i} P_{sub}{}^{i} (1-P_{sub})^{l-i}, \tag{4}$$

where $i = 0$ in equation (4) denotes that no STA successfully transmits RTS in this time slot caused by no RTS transmitting or all RTS transmitting is collided by other RTS. The probability that no STA transmits RTS and the probability that each transmitting RTS collide with other RTS is given by

$$P_{idle} = (1-\tau)^{n \cdot l}, \tag{5}$$

$$P_{col} = (1-P_{sub})^l - P_{idle}. \tag{6}$$

The mean successful RTS transmission number is given by

$$N_{suc} = \frac{\sum_{i=1}^{l} P_{suc}(i) \cdot i}{\sum_{i=1}^{l} P_{suc}(i)}. \tag{7}$$

C. Saturation Throughput

For each time slot, there are three states: idle time slot, collision time slot and successful transmission time slot. First of all the duration for each state need to be calculated

$$T_{idle} = \sigma, \tag{8}$$

$$T_{col} = T_{RTS} + T_{DIFS}, \tag{9}$$

$$T_{suc}(i) = T_{DIFS} + T_{RTS} + T_{G-CTS}(i) + T_{DATA}(i) + T_{G-ACK}(i) + 3 \cdot T_{SIFS}, \tag{10}$$

where σ is time slot, T_{RTS} is the time duration of transmitting RTS, and T_{DIFS} and T_{SIFS} are the DIFS duration and short inter frame space (SIFS) duration. The $T_{G-CTS}(i)$, $T_{DATA}(i)$ and $T_{G-ACK}(i)$ ($i \in [1, l]$) denote the transmission time of G-CTS, DATA and G-ACK when i STAs successfully transmit RTS.

At last the saturation throughput is given by

$$S = \frac{\sum_{i=1}^{l} P_{suc}(i) i E}{P_{idle} T_{idle} + P_{col} T_{col} + \sum_{i=1}^{l} P_{suc}(i) T_{suc}(i)}, \tag{11}$$

where E is the DATA payload in one transmission for one STA.

IV. PERFORMANCE EVALUATION

To evaluate the performance of our proposed OMAX, a simulation platform based on NS2[17] is established. The channel is assumed in ideal conditions so that the performance of proposed OMAX is more easier to examine. Adaptive modulation and coding (AMC) is not used, and fixed modulation and coding scheme (MCS) is used in each simulation for DATA transmission, while fixed BPSK modulation and 1/2 coding is used for control packet for all of the simulation. The MCS in 40MHz bandwidth is illustrated in TABLE I.

TABLE I. MODUATION AND CODING SCHEME IN 40MHZ

Index	Modulation	Coding	Data Rate(Mbps)
1	QPSK	1/2	27.0
2	QPSK	3/4	40.5
3	16QAM	1/2	54.0
4	16QAM	3/4	81.0
5	64QAM	2/3	108.0
6	64QAM	3/4	121.5
7	64QAM	5/6	135.0

A. Performance Comparation with DCF

In this sub-section, the performance between OMAX and DCF is compared. The simulation parameters is shown in TABLE II. The whole channel bandwidth is 40MHz, and the sub-channel number is 8 for 5MHz sub-channel bandwidth or 16 for 2.5MHz sub-channel bandwidth.

TABLE II. SIMULATION PARAMETERS I

Parameter	Value in Simulation
Channel Bandwidth	40MHz
Sub-channel Bandwidth	5MHz or 2.5MHz
Sub-channel Number	8 or 16
The number of STAs	100
DATA MAC Header Duration	32us
DATA PHY Header Duration	28us
DATA Packet Length	1500Bytes
Control Packet PHY Rate	6Mbps
DATA packet PHY Rate	27, 40.5, 54, 81,108, 121.5, 135Mbps
CWmin	15
CWmax	1023
Number of STAs	100
DIFS	34us
SIFS	16us
Slot Time	9us

Fig. 5 depicts the saturated throughput of OMAX with different sub-channel number and DCF protocol for different PHY rate. This shows that the proposed OMAX protocol could always deliver a higher throughput than DCF. When the physical rate is 135Mbps, OMAX with 16 sub-channels improves throughput to 160% comparing with DCF. It is obviously that the throughput could be further improved by dividing channel into more sub-channels. The MAC efficiency of both OMAX and DCF decrease with increasing PHY rate in Fig. 6, but OMAX maintains better performance than DCF. Moreover, the analysis result of OMAX match the simulation result very well.

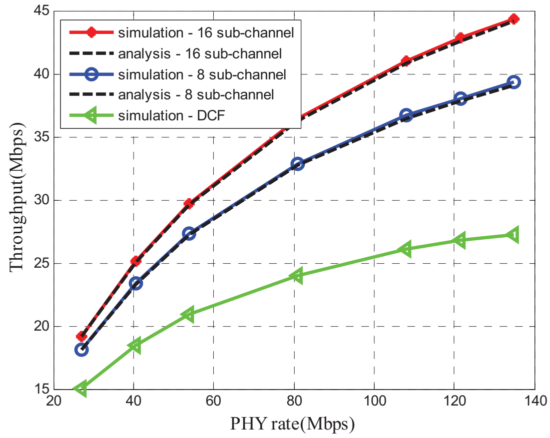

Fig. 5. Saturation throughput comparation between OMAX and DCF.

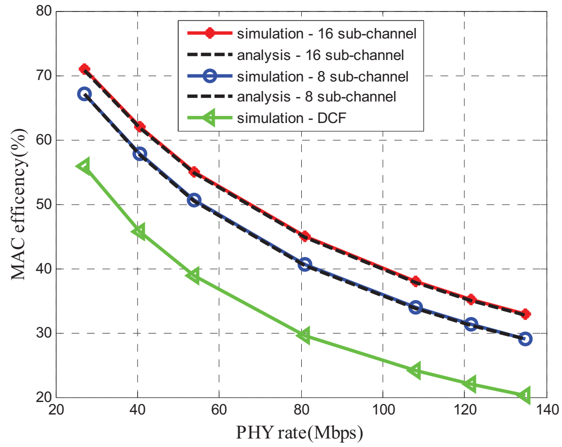

Fig. 6. MAC efficiency comparation between OMAX and DCF.

B. The Impact of CWmin

In this sub-section, the impact of CW_{min} is examined for both throughput result and average number of accessing STAs. The simulation parameters is as same as in TABLE II, and the differences are that PHY rate is fixed as 54Mbps, and CW_{min} is variable.

Fig. 7 and Fig. 8 depict the saturated throughput and average number of accessing STAs in OMAX protocol for different CW_{min} value. It is clear that for certain scene there is one optimal operating point of CW_{min} value, for example, in Fig. 7 the optimal operating point appears when CW_{min} value is 15. And the average number of accessing STAs is proportional to the saturated throughput. In other word, the reason of increasing throughput is multiple user access gain. Moreover, the analysis result of OMAX match the simulation result very well. It is also interesting that the saturated throughput is in a good performance in a range of CW_{min} value (from CW_{min} value

7 to 127). This, therefore, is also an advantage of proposed OMAX protocol.

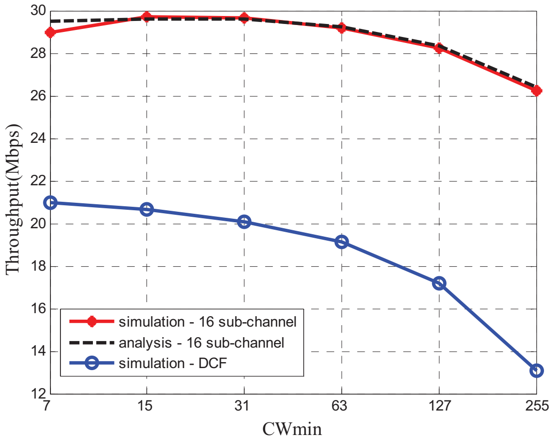

Fig. 7. Saturation throughput with variable CWmin.

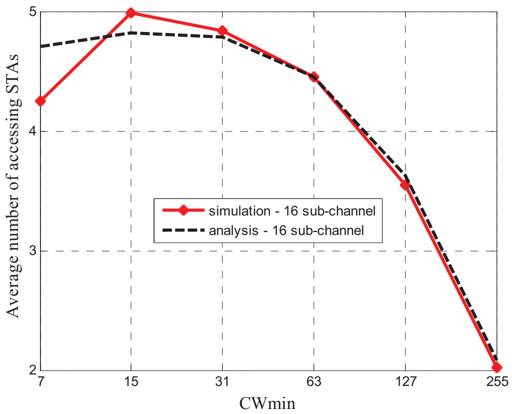

Fig. 8. Average number of accessing STAs with variable CWmin.

V. CONCLUTION

An OFDMA based multiuser access for IEEE 802.11ax named OMAX protocol is proposed for next generation WLANs in this paper. The frame work of OMAX is described in detail. In OMAX, whole channel physical channel sensing and fast backoff process is proposed to solve synchronization problem, and enhanced RTS/CTS mechanism and frame structure is designed to reduce overhead. The theoretical analysis of the OMAX protocol is discussed. Moreover, the simulation result shows that comparing with DCF, OMAX increases the throughput to 160%. In the future work, multiple user MIMO could be introduce to OMAX framework to further improve the performance of next generation WLANs. Furthermore, the impact of overlapping BSS to OMAX is also an important topic for deep study.

VI. ACKNOWLEDGEMENT

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