Performance Analysis of the 802.11ax UL OFDMA Random Access Protocol in Dense Networks

Leonardo Lanante Jr, Hiroshi Ochi
Tatsumi Uwai, Yuhei Nagao, Masayuki Kurosaki
Computer Science and Systems Engineering
Kyushu Institute of Technology
Iizuka, Fukuoka 820-8502
Email: leonardo@cse.kyutech.ac.jp

Chittabratta Ghosh
Intel Corporation
2200 Mission College Blvd.,
Santa Clara, CA 95054
Email: chittabrata.ghosh@intel.com

***Abstract*—Recently, 802.11ax has introduced uplink Orthogonal Frequency Division Multiple Access (UL OFDMA)-based random access transmission to provide uplink multiuser capability to stations (STA) with unknown buffer status. These STAs include those that are waking up from sleep and unassociated STAs trying to establish connection for the first time. Due to the absence of carrier sensing per resource unit, this procedure has a maximum efficiency of only about 37% for high number of STAs. The efficiency will decrease further without properly choosing the random access parameters. In this paper, we first build an analytical model of the performance of UL OFDMA random access transmission and verify it using simulations. In addition, we propose methods to optimize various random access parameters to maintain a system efficiency near the 37% limit. Simulation results show that our optimization methods can increase the throughput of UL OFDMA random access by as much as 39% when compared to randomly chosen parameters.**

1. Introduction

Uplink (UL) multiuser (MU) transmission using orthogonal frequency division multiple access (OFDMA) and UL multiple input multiple output (MIMO) are two key technologies approved by the 802.11ax task group to improve the system throughput of wireless local area networks (WLAN) in dense environments [1]. Both methods effectively increase the efficiency of the UL transmission which is low due to the small packet sizes characteristic of the UL channel [2].

In order to facilitate UL MU, the 802.11ax specification framework defines a control frame called the trigger frame(TF). The TF serve as a synchronization mechanism for UL MU as well as a transport for the resource unit (RU) allocations. In situations when a station (STA) has just woken up from sleep or if a STA is still unassociated, the AP does not know its current buffer status. Hence the AP cannot provide any RU allocation for these cases reducing the opportunities for the efficiency offered by UL MU.

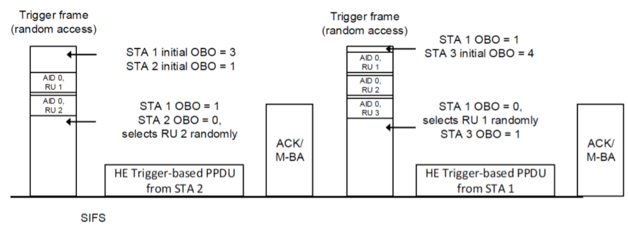

Figure 1. 802.11ax UL OFDMA-based random access procedure [1]

To allow STAs with unknown buffer status to participate in UL MU via UL OFDMA, the random access procedure has been defined as shown in Fig. 1. In this protocol, the AP allows random access for some RUs identified by a NULL association identifier (AID) value (i.e. AID=0), instead of a STA identifying AID. Any STA receiving the TF without an RU associated to it can access exactly one random access RU provided it completes a back off (BO) procedure similar to the legacy distributed coordinating function(DCF) exponential BO procedure. In [3], the authors proposed a pre-draft standard analysis of the 802.11ax UL-OFDMA random access procedure. This was done recognizing that in some special conditions, the equivalent Markov model of the UL OFDMA random access protocol is mathematically equivalent to the DCF Markov model first appeared in [4]. One of these conditions require that the minimum random access contention window is higher than the number of RUs and is a multiple of it. Unfortunately, based on the latest 802.11ax draft amendment [1], unlike contention window parameters which are always a multiple of 2, the number of resource units are arbitrary and hence more often than not follow a completely different state machine. The main contribution of this paper is thus the generalized Markov model analysis of the 802.11ax UL OFDMA Random access protocol.

Even before 802.11ax, several UL MU medium access protocols and their analysis have been proposed in literature [5], [6], [7]. In [5], the authors proposed a transmission request phase prior to the actual UL MU transmission. In the transmission request (TR) phase, each STA perform carrier sense in their allotted subcarrier. However, per subcarrier sensing is not mandatory in 802.11ax due to the difficulty of its implementation. This is the reason why [5] cannot be used as a UL MU protocol in 802.11ax.

In [6], the authors proposed a multiround contention protocol where multiple request to send (RTS) packets are accepted by the AP in a fixed time duration. Guided by a stopping condition, the AP then sends a group clear to send (G-CTS) frame which functions exactly the same as the TF in 802.11ax. A similar approach is proposed in [7] where instead of a fixed duration, the protocol refreshes the waiting time for the next RTS frame every time an RTS frame is received by the AP. In this way, the number of STAs allowed will not be limited by a fixed time duration leading to a higher number of STAs that can participate in UL MU. In both approaches, the use of RTS prior to controlled transmission does not make use of the ability of the 802.11ax device to transmit in a channel width much smaller than 20MHz (about 2MHz for the smallest RU in 802.11ax).

The rest of the paper is structured as follows. In section 2, we discuss the 802.11ax UL OFDMA random access procedure. In section 3, the analytical model is described. The model validation is shown section 4 by comparing it to simulation results. The proposed optimization scheme are then presented in section 5. Lastly, we conclude the paper in section 6.

2. 802.11ax Random Access OFDMA

This section briefly summarizes the 802.11ax Random Access protocol. For a more complete and detailed information regarding the protocol, the reader is referred to the 802.11ax draft amendment document [1].

For the purpose of analyzing the performance of random access OFDMA, we assume a basic service set (BSS) with one AP which continuously sends TF with r random access RUs to n STAs with transmit buffers that are always full.

Each participating STA that receives the TF with random access RUs first generates a random OFDMA backoff (OBO) count, if it currently doesn't have one before it can access any random access RU. The STAs would then decrement its OBO counter for every random access RUs present in the received TF. As shown in Fig. 1, when a STA's OBO count reaches zero, the STA gains random access rights and send a frame to one random access RU it randomly chooses. The receipt of an acknowledge (ACK) frame from the AP signifies success of that transmission. Any STA that doesn't finish its current OBO count would resume its count in the next random access TF.

Similar to the legacy 802.11 DCF, the random access UL OFDMA adopts an exponential backoff. At each fresh attempt to packet transmission, the OBO count is uniformly chosen in the range of $(0, w)$ where w is the OFDMA contention window (OCW) and depends on the number of failed transmissions encountered for the packet. At first transmission, w is set to the minimum contention window. After each unsuccessful attempt, w is updated to $2 \times w + 1$ until it reaches the value of $\mathrm{OCW}_{\max} = 2^m(\mathrm{OCW}_{\min} + 1) - 1$ for a total of m OBO stages. Succeeding retransmissions after m will still use $\mathrm{OCW}_{\max}$ as the contention window.

In Fig. 1, the HE Trigger based PPDU frames refer to the UL MU frames that random access STAs transmit after finishing their OBO count. In general, this also includes transmissions from STAs with an allocated RU. In this paper however, unless otherwise specified, TFs only contain random access RUs.

To simplify the notations we define

$$W = \mathrm{OCW}_{\min} + 1 \tag{1}$$
$$W_i = 2^i W \tag{2}$$

as the number of possible OBO counts in the first and successive backoff stages respectively.

The AP using its beacon frame advertises the current values of $\mathrm{EOCW}_{\min}$ and $\mathrm{EOCW}_{\max}$ for the STA to adjust the value of $\mathrm{OCW}_{\min}$ and $\mathrm{OCW}_{\min}$ such that

$$\mathrm{OCW}_{\min} = 2^{\mathrm{EOCW}_{\min}} - 1 \tag{3}$$
$$\mathrm{OCW}_{\max} = 2^{\mathrm{EOCW}_{\max}} - 1 \tag{4}$$

3. Analytical Model

3.1. Transmission/Collision Probability

The transmit probability of the random access UL OFDMA mechanism can be easily computed using the steady state assumptions employed in [4]. With this assumption, each STA's state is independent of the state of the other STAs making the collision probability constant at all OBO stages. This assumption gets increasingly more accurate with higher number of STAs and W.

Using the definitions and conventions in [4], let $b(t)$ and $s(t)$ be the stochastic processes representing the OBO stage and the OBO state respectively for a STA for some time slot t. A discrete-time Markov chain in Fig. 2 is used to model the bi-dimensional process $\{b(t), s(t)\}$. Let $b_{i,k} = \lim_{t\to\infty}\{s(t) = i, b(t) = k\}$ be the stationary distribution of the Markov chain, where $i \in [0, m]$, $k \in [0, W_i - r - 1]$. We have the following relations:

$$\begin{aligned} b_{i,0} &= p \cdot b_{i-1,0} \quad , \qquad 0 < i < m \\ &= p^i \cdot b_{0,0} \end{aligned} \tag{5}$$

Also, from Fig. 2,

$$\begin{aligned} b_{m,0} &= b_{m-1,0} \cdot p + b_{m,0} p \\ &= \frac{p^m}{1-p} b_{0,0} \end{aligned} \tag{6}$$

In random access UL OFDMA, STAs transmit when the backoff counts are within 0 up to r, where r is the number of RUs. To model this, remaining OBO counts from 0 to r are considered transmit states meaning that they will transmit in the next TF containing r random access RUs. This is why there are only a total of $W_i - r$ states for every stage in

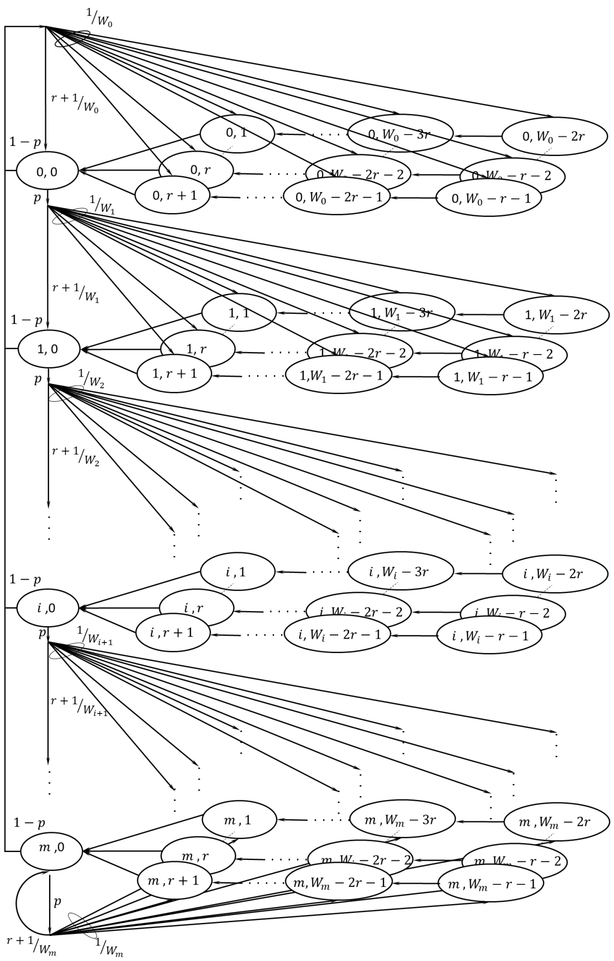

Figure 2. Markov chain model

the Markov model shown in Fig. 2 as opposed to the W_i possible OBO counts. Owing to the chain regularities, it can be shown that for each $k \in \{0, W_i - r\}$

$$b_{i,k} = b_{i,0} q_{i,k} \tag{7}$$

where

$$q_{i,k} = \begin{cases} \frac{\left(\lfloor \frac{W_i - 1}{r} \rfloor + 1\right) \cdot [(W_i - 1) \bmod r] + 1}{W_i}, & k = 0 \\ \frac{\lceil \frac{W_i - k - r}{r} \rceil}{W_i}, & 0 < k \leq W_i - r - 1 \end{cases} \tag{8}$$

Imposing the normalization condition, we get

$$1 = \sum_{i=0}^{m} \sum_{k=1}^{W_i} b_{i,k} = \sum_{i=0}^{m} b_{i,0} \sum_{k=1}^{W_i} q_{i,k} = \sum_{i=0}^{m} b_{i,0} Q_i \tag{9}$$

In the trivial case when $W_i - 1 \leq r$, it is easy to show that $Q_i = 1$. When $W_i - 1 > r$, Q_i can be computed using elementary counting techniques. By decomposing $W_i - 1$ such that

$$W_i - 1 = \alpha_i r + \beta_i \tag{10}$$

TABLE 1. CLOSED FORM SOLUTIONS TO Q_i FOR $r \in (1, 2, 4, 6, 9)$ WHEN $W_i - 1 > r$

r	Q_i
1	$Q_i = \frac{W_i^2 - W_i + 2}{2W_i}$
2	$Q_i = \frac{W_i^2 + 4}{4W_i}$
4	$Q_i = \frac{W_i^2 + 3W_i + 2}{6W_i}$
6	$Q_i = \frac{W_i^2 + 4W_i + 2(-1)^{log_2 W_i} + 14}{12W_i}$
9	$Q_i \approx \frac{W_i^2 + 7W_i + 28}{18W_i}$

where α_i and β_i are non-negative integers and $\beta_i < r$ for all i, it can then now be shown that

$$Q_i = \frac{(\alpha_i + 1)\alpha_i r + 2(\alpha_i + 1)\beta + 2}{2W_i}. \tag{11}$$

for any value of i and r. Table 1 shows closed form solutions to Q_i for some chosen r.

Based on the W, m and r, computing the transmit probability τ involves three cases as follows:

1. $W_m - 1 \leq r$

When $W_m - 1 \leq r$, the maximum OBO count possible is less than r. Hence in this case, the chosen OBO count and OBO stage becomes irrelevant as all active STAs transmit simultaneously after any TF in one of the r RUs. This is very similar to a slotted ALOHA medium access scheme where instead of defined time slot boundaries, transmissions occur whenever a TF is received. Following the definitions mentioned above, it is intuitive that $q_{i,0} = 1$. Consequently, $Q_i = 1$ and from the normalization condition

$$1 = \sum_{i=0}^{m} b_{i,0} Q_i = \sum_{i=0}^{m} b_{i,0} = \tau \tag{12}$$

2. $W - 1 \geq r$

Without loss of generality, from here on, we only describe the special case when r is a power of 2 for the sake of brevity. When r is less than or equal to W, then all values of Q_i will depend on the specific value of r as shown in (11). This condition results in a Q_i in the general form

$$Q_i = \frac{W_i^2 + (r-2) \cdot W_i + 2r}{2rW_i}. \tag{13}$$

From (5), (9) and (13),

$$1 = \sum_{i=0}^{m} b_{i,0} \frac{W_i^2 + (r-2)W_i + 2r}{2rW_i} \tag{14}$$

$$= \frac{b_{00}}{2r(1-p)} A \tag{15}$$

where

$$A = W \frac{1 - p - p(2p)^m}{1 - 2p} + r - 2 + \frac{2r}{W} \cdot \frac{1 - p + \frac{p}{2}(\frac{p}{2})^m}{1 - \frac{p}{2}} \tag{16}$$

Then, from (5) and (6)

$$\tau = \sum_{i=0}^{m} b_{i,0} = \frac{b_{0,0}}{1-p} = \frac{2r}{A} \tag{17}$$

For r not equal to a power of 2, (13) is replaced by the appropriate expression for Q_i such as those listed in Table 1.

3. $W - 1 < r < W_m - 1$

First we define $c = \lfloor \log_2(r) \rfloor$ as the last OBO stage when the contention window is lower than r. In this case, backoff stages from 0 to c results in $Q_i = 1$ just as in case 1 while stages $c+1$ onwards follow (13) just like as in case 2.

From (9),

$$1 = \sum_{i=0}^{c} b_{i,0} + \sum_{i=c+1}^{m} b_{i,0} \frac{W_i^2 + (r-2)W_i + 2r}{2rW_i} \tag{18}$$

$$\begin{aligned} &= \sum_{i=0}^{c} b_{i,0} + \sum_{i=0}^{m} b_{i,0} \frac{W_i^2 + (r-2)W_i + 2r}{2rW_i} \\ &\quad - \sum_{i=0}^{c} b_{i,0} \frac{W_i^2 + (r-2)W_i + 2r}{2rW_i} \end{aligned} \tag{19}$$

$$= \frac{b_{0,0} B}{2r(1-p)} \tag{20}$$

where

$$\begin{aligned} B = A - W \frac{1 - p - (2p)^{c+1} + p(2p)^{c+1}}{1 - 2p} \\ + (r+2)(1 - p^{c+1}) - \frac{2r}{W} \cdot \frac{1 - p - (\frac{p}{2})^{c+1} + p(\frac{p}{2})^{c+1}}{1 - (\frac{p}{2})} \end{aligned} \tag{21}$$

Finally,

$$\tau = \sum_{i=0}^{m} b_{i,0} = \frac{b_{0,0}}{1-p} = \frac{2r}{B} \tag{22}$$

In all three cases, assuming uniformly distributed random access transmit RU selection, the collision probability can be written as

$$p = 1 - (1 - \frac{\tau}{r})^{n-1} \tag{23}$$

Given the equations for transmit probability (12, 17, 22) and collision probability (23), in each case we have a system of two nonlinear equations with two unknowns. Hence the corresponding transmit and collision probabilities can be solved using various numerical methods and is outside the scope of this paper.

3.2. Efficiency and Throughput

The RU efficiency of UL OFDMA random access scheme can be thought of as the average probability that exactly one STA transmits in one RU over all transmitted TFs. In uniformly random selection of random access RU, this is equal to

$$\eta = n \frac{\tau}{r} (1 - \frac{\tau}{r})^{n-1} \tag{24}$$

Using the above equation, it is easy to show that the maximum RU efficiency is achieved when

$$\tau_{max} = \frac{r}{n}. \tag{25}$$

The maximum RU efficiency achieved is numerically equal to slotted ALOHA's maximum efficiency of $1/e \approx 37\%$ for large number of users [8]. This result has an intuitive practical significance. When the n is known with some accuracy, setting the value of number of RUs to $r > n$ will always be inefficient due to the greater than unity required transmit probability.

The average throughput on the other hand can be expressed as

$$S = \frac{\eta r E[P]}{T_{wait} P_{wait} + T_s (1 - P_{wait})} \tag{26}$$

where $E[P]$ is the average number of bits sent in an RU, T_{wait} is the time duration spent when no STAs transmit after a TF, and T_s is the time duration spent when at least one STA transmit in at least one RU. P_{wait}, the probability that no STA transmit in any RU is equal to

$$P_{wait} = (1 - \tau)^n. \tag{27}$$

Also, based on Fig. 1,

$$T_s = T_{TF} + 3T_{SIFS} + T_{TXOP} + T_{MBA} \tag{28}$$

$$T_{wait} = T_{TF} + T_{TO} \tag{29}$$

where T_{TF}, T_{SIFS}, T_{TXOP}, T_{MBA} and T_{TO} refers to the TF time, SIFS time, TXOP time and Multi STA Block ACK, and time out durations. For large number of users the denominator in (26) can be approximated as a constant and hence the maximum throughput is also approximately achieved when $\tau = \tau_{max}$.

When the PHY rate, roughly equivalent to $Rate = \frac{E[P]}{T_{TXOP}}$ is used to normalize S, the medium access control (MAC) efficiency can be obtained as follows

$$E_S = \frac{S}{Rate} \approx \frac{\eta}{1 - (1 - \tau)^n} \tag{30}$$

resulting in a value approximately equal to the RU efficiency divided by a factor equal to the probability that any transmission is occurring on the channel. When the maximum efficiency occurred at a relatively low τ, MAC efficiencies above 37% can be achieved. This is why legacy DCF MAC efficiencies of above 70% are common. However in UL OFDMA random access, unless $r = 1$, the probability that transmissions are occurring in the channel is very high such that in most cases, the maximum efficiency is equal to 37%.

4. Model Validation

To validate the proposed analytical model, we compared its results to a simulation model programmed in Matlab and was calibrated using the simulation scenarios adopted by the 802.11ax task group [9]. These simulation scenarios are based on empirical measurements and are hence very close

TABLE 2. SIMULATION PARAMETERS

Parameter	Value
Packet Size	380 octets
PHY preamble length	40μs
Timeout	16μs
Trigger Frame Length	100μs
RU Data Rate	0.8Mbps
Multiuser BA length	68 μs
SIFS time	16μs

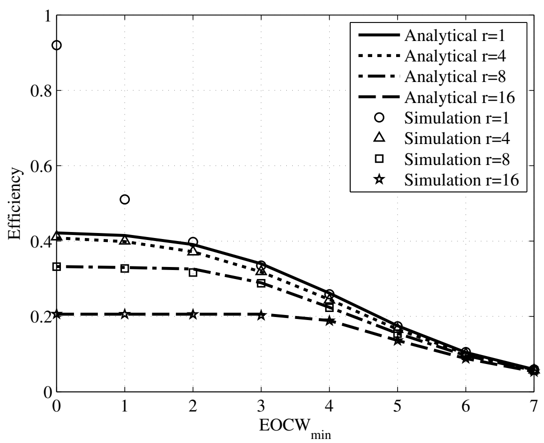

Figure 3. Efficiency vs. minimum contention width

to the actual conditions where 802.11ax will be deployed. The simulation parameters are summarized in Table 2.

In Fig. 3, we show the efficiency results for both simulation and analytical models for $r = \{1, 4, 8, 16\}$. In these set of results, we assume $n = 4$, and $\mathrm{EOCW}_{\max} = 7$. Based on the figure, we can see that the accuracy of the proposed analytical model closely follows the simulation results for all values of $\mathrm{EOCW}_{\min}$ and r except for low values of $\mathrm{EOCW}_{\min}$. In the figure, this happens when $\mathrm{EOCW}_{\min} \in \{0, 1\}$ and $r = 1$. The higher than expected efficiency is due to the channel capture that occurs when one or two STAs monopolizes the channel which prevents other STAs from transmitting. Note that this situation violates the steady state assumption made in section 3 to model the random access process.

In Fig. 4, we set $\mathrm{EOCW}_{\min} = 0$, and $\mathrm{EOCW}_{\max} = 7$ representing the absolute minimum and maximum values of OCWs currently allowed by 802.11ax. In this figure, we can confirm the accuracy of the proposed analytic model even for low number of STAs as long as the number of resource units is sufficient to prevent one STA from monopolizing the channel via channel capture. While lesser in extent, it is also apparent in the figure the same trend in legacy DCF where an increase in the number of STAs results in a corresponding increase in collisions and hence reduction of the system efficiency. A unique feature of UL OFDMA random access protocol however is that it can dynamically increase the number of resource units to accommodate the increase in n.

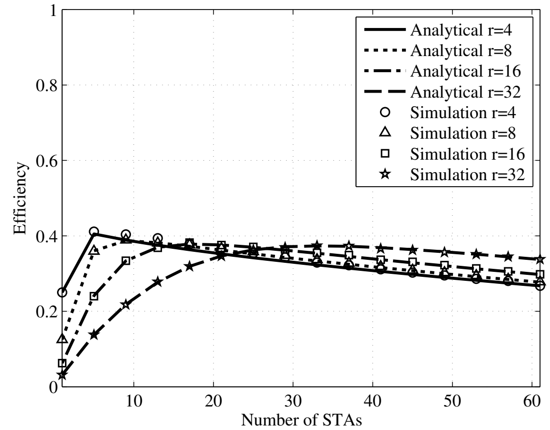

Figure 4. Efficiency vs. Number of STAs

5. Throughput Optimization Algorithm

In this section, we propose an optimization algorithm for achieving optimal efficiency by varying the number of resource units and contention window parameters. To do this, we assume that an accurate estimate of the number of STAs $\tilde{n}$ is available in the AP. One way of obtaining this information is by counting the actual number collisions per RU and then estimate n from (23). In order to reduce the latency as much as possible without affecting the throughput, we choose $r = R$ equal to the largest possible number of RUs to minimize the needed $\mathrm{OCW}_{\min}$. However, it cannot be more than $\tilde{n}$ as mentioned in Section 3.2. Hence we choose

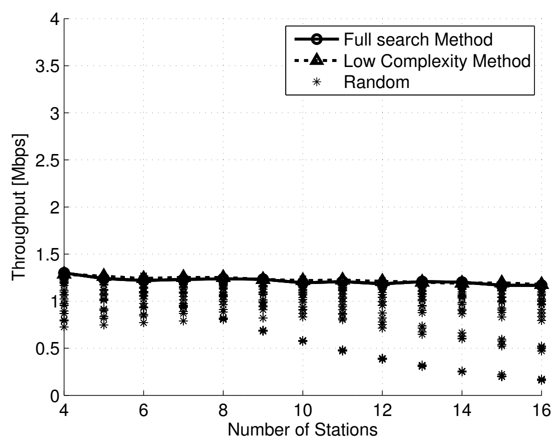

Figure 5. Throughput vs. Number of STAs

$$r = \begin{cases} n, R \geq n \\ R, otherwise \end{cases} \tag{31}$$

When $R \geq n$, there are enough RUs for all STAs making contention unnecessary. Thus, the AP can disable contention

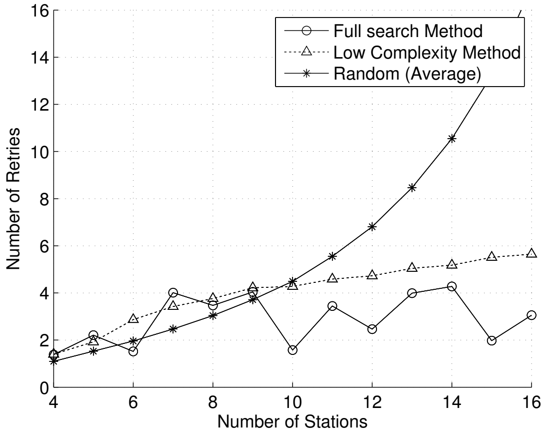

Figure 6. Number of Retransmissions vs. Number of STAs

by setting $W = 0$, and $m = 0$. When $R < n$ on the other hand, the AP needs calculate a following joint optimization problem to choose W and m.

$$\{\tilde{W}, \tilde{m}\} = \arg\max_{W,m} S \tag{32}$$

A low complexity version of this algorithm is done by setting $\mathrm{EOCW}_{\min} = 0$ and then computing an estimate of m using

$$\tilde{m} = \arg\min_{m} \left| \frac{2r}{B(1-p)} - \frac{r}{n} \right| \tag{33}$$

The low complexity algorithm works well when there are only a few STAs expected which would normally result in a small value $\mathrm{EOCW}_{\min}$. Compared to the full search method whose complexity is $O(n^2)$ with the range of $\mathrm{EOCW}_{\min}$, the low complexity algorithm is only $O(n)$ which is useful in real-time implementation.

In Figs. 5 and 6, we apply the theoretical results above to set the access parameters of the random access simulations. Fig. 5 shows the performance of the proposed optimization algorithm for both full search method and low complexity method when $R = 4$. Both algorithms clearly outperform the performance of the systems with fixed value of W and m that are randomly chosen. In addition, both methods' throughputs have corresponding MAC efficiencies that are virtually equal to the 37% limit. Depending on the number of users, the proposed methods can give about $10\% - 39\%$ higher throughput on average compared to randomly chosen parameters.

In Fig. 6, the average retransmissions per STA are shown. This value affects the total latency that a STA will experience in trying to access the channel via random access. This figure shows the real advantage of the full search method in that by choosing accurately the $\mathrm{EOCW}_{\min}$, each STA can transmit its packet with as little retransmissions needed. For large number of users, the full search method only requires 2 or 3 retransmissions on average to successfully send a packet.

6. Conclusion

In this paper, we have presented an analytical model to compute the efficiency and throughput of UL OFDMA random access protocol of the 802.11ax standard. The proposed model supports an arbitrary number of resource units, contention window parameters and number of STAs. It can be used to design algorithms for adjusting OCW parameters to achieve optimal throughput at all times. As a proof of concept, the paper introduced two algorithms that optimizes the throughput. While both have the same performance in terms of maximizing the throughput, the full search method results in lesser retransmission by jointly selecting the minimum OCW with the maximum OCW. Future works include a much more rigorous treatment on the throughput and latency especially in mixed DCF and UL OFDMA case. In addition, the impact of estimation errors of the number of STAs is of great interest as this parameter may change dynamically every TF.

Acknowledgments

This work was partly supported by Grant-in-Aid for Young Scientists (B)15K18067

References

[1] ”$IEEEP802.11ax^{\mathrm{TM}}$/D0.5 Amendment 6: Enhancements for High Efficiency WLAN,” the 802.11 Working Group of the 802 Committee, 2016.

[2] J. Lansford,“IEEE 802.11ax High Efficiency WLAN Packet measurements around Boulder, CO,”IEEE 802.11-14/0546r1, May. 2014.

[3] T. Uwai, T. Miyamoto, Y. Nagao, L. Lanante Jr., M. Kurosaki, and H. Ochi, “Adaptive Backoff Mechanism for OFDMA Random Access with Finite Service Period in IEEE802.11ax,” in *Proc. IEEE CSCN 2016*, Nov. 2016

[4] G. Bianchi,’Performance analysis of the IEEE 802.11 distributed coordination function,’ IEEE J. Select. Areas Commun., vol. 18, no. 3, pp. 535–547, Mar. 2000.

[5] Y. P. Fallah, S. Khan, P. Nasiopoulos and H. Alnuweiri, ”Hybrid OFDMA/CSMA Based Medium Access Control for Next-Generation Wireless LANs,” Communications, 2008. ICC ’08. IEEE International Conference on, Beijing, 2008, pp. 2762-2768.

[6] Y. J. A. Zhang, ”Multi-round contention in wireless LANs with multipacket reception”, IEEE Transactions on Wireless Communications, vol. 9, no. 4, pp. 1503-1513, 2010

[7] B. Er-Rahmadi, A. Ksentini and D. E. Meddour, ”Wait-to-pick-as-available (W2PAA): A new MAC protocol for uplink multi-users transmissions in WLAN,” Wireless and Mobile Computing, Networking and Communications (WiMob), 2015 IEEE 11th International Conference on, Abu Dhabi, 2015, pp. 802-808.

[8] W. Crowther (January 1973). ”A System for Broadcast Communication: Reservation-ALOHA”. Proceedings of the 6th Hawaii International Conference on Systems Sciences. Honolulu. pp. 371374.

[9] IEEE802.11ax document 11-14-0980, Simulation Scenarios, available at https://mentor.ieee.org/802.11/dcn/14/11-14-0980-16-00ax-simulation-scenarios.docx