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802.11ax 基於 OFDMA 隨機接取效能分析
Performance Analysis of IEEE 802.11ax OFDMA-based Random Access

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本論文係楊行君 (R03942126) 在國立臺灣大學電信工程學研究所完成之碩士學位論文，於民國 105 年 12 月 19 日承下列考試委員審查通過及口試及格，特此證明

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感謝…

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I'm glad to thank…

摘要

近年來 wifi 成為分布最為廣泛的 WLAN，wifi 配置地越來越多，越來越密集，也有越來越多的設備接入 wifi，通過 wifi 的流量也越來越大。漸漸地，傳統 802.11 接取層（MAC）基於分布式競爭接入（DCF）的方式本身的問題越來越凸顯出來，主要表現為碰撞加劇，從而網路吞吐量降低，接入時延變大，能耗嚴重。我們稱之為密集分布場景（dense deployment scenario）的問題，所以 IEEE 802.11 成立 ax 工作組針對密集分布場景的問題，在傳統 802.11 接取層（MAC）和物理層（PHY）都進行很大的修改。引入了 OFDMA，實現多用戶信道（MU）。802.11ax 提出基於 OFDMA 的隨機接取，它比傳統的隨機接取更加覆雜，更有彈性。本論文旨在分析該機制的效能，建立二維離散時間馬爾可夫模型很好地描述了其穩定狀態行為。並且借此模型分析重要系統參數對系統效能的影響從而得出配置參數的方法。

關鍵詞：802.11ax，多用戶信道，OFDMA，隨機接取

Abstract

In recent years, WiFi has been the most extensively deployed WLAN. With more and more deployment, devices or users, and exploding traffic, the WLAN is more and more dense. Gradually, problem from the nature of distributed coordination function (DCF), which is the foundation of legacy 802.11 MAC, has arisen and is becoming more and more severe. That is, severe collision causes degradation of throughput, defer access, and waste energy of stations, which in total is called dense deployment problem. Thus, task group IEEE 802.11ax, which was set up in 2014 confronting the above problem, makes revolutional modification of both MAC and PHY to legacy 802.11. OFDMA is issued in 802.11ax, implementing Multi-User (MU) channel. And correspondingly, 802.11ax proposes OFDMA-based random access, which is more complicated and flexible than legacy random access. This work model the OFDMA-based random access with bi-dimensional discrete-time Markov Chain to accurately depict its steady state behavior. With this model, we evaluate the effect of several system parameters and propose rules of configuring the parameters.

Keyword: 802.11ax, MU PHY, OFDMA, random access

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Chapter 1

Introduction

During last decades, IEEE 802.11 achieved great success in WLAN. Enormous WiFi are deployed for its high speed and simplicity of deployment. The foundation of 802.11 MAC, distributed coordination function (DCF), is a random access mechanism [2]. With DCF, a random access MAC, the star topology of a 802.11 WLAN result in a absolutely unfair queueing. Since in star topology, access point (AP) needs to transmit all the down-link (DL) traffic, which is often more than $1/2$ traffic loading of the basic service set (BSS), while AP has only $1/n$ chance to access medium where n is number of total stations including AP. It is, thus, an unfair queueing problem. What's worse, combining effect of the unstability of random access's nature and the unfair queueing problem, once under a dense scenario, the performance will degrade severely since contention and collision will occupy the channel. That lies the defect of legacy 802.11. We collectively call them dense deployment problem. The dense deployment problem not only degrades throughput but also waste much energy.

Previous amendments, 802.11n and 802.11ac called high throughput (HT) and very high throughput (VHT) respectively which are aimed at improving throughput, only mitigate the dense deployment problem. The bottleneck at the MAC efficiency is not resolved. Thus, 802.11ax task group is issued targeted at high efficiency WLAN (HEW), improving quality of experience (QoE) and power save. Confronting the dense deployment problem, 802.11ax permits AP of central control, to schedule both down-link (DL) and up-link (UL) transmission so that contention is much reduced and unfair queueing problem could be resolved. IEEE 802.11ax also issues multi-user (MU) PHY which is supported with Orthogonal Frequency Multiple Access (OFDMA), and a special control frame called trigger frame (TF) to implement trigger-based MU UL[1]. Accordingly, multi-channel random access, the focus of this paper, is of course implemented in 802.11ax, named OFDMA-based random access, since random access is an efficient way for stations to transmit bandwidth request, buffer status report (BSR) etc. Actually, the new MAC is based on DCF since it helps co-exist among BSS and other systems. The difference is that the DCF mainly works on AP which means AP needs to access channel following DCF procedure, while HE-STA (802.11ax STA) is mostly scheduled by AP and even the random access procedure is initialized by AP.

Random access is a classical topic in data network which has evolved multiple variants with various physical layer. Random access originates from Aloha and slotted Aloha in single-user channel. Then CSMA works as typical collision resolution [5], which is accepted by IEEE 802.11 named CSMA/CA. The backoff mechanism, which is about retransmission when failure occurs, is also important in random access. Random access has been a popular approach to MAC on unlicensed band for a long time, while cellular network only implements random access for initial up-link access. With OFDMA, i.e., MU channel, randomness extends from time domain to frequency domain, 2-dimension. In cellular network, IEEE 802.16 and 3GPP LTE use a multi-channel slotted Aloha. In the literature, plenty of works focus on the multi-channel random access, and most of them work on cellular network. [3] designs a 1-persistent type retransmission, i.e., no exponential backoff, to achieve a fast access. In [9], a closed-form expression of throughput for OFDMA system is firstly given. Many works compare performance of two backoff mechanism, binary exponential backoff and uniform backoff [9] [7] [4], which are implemented by IEEE 802.16 and 3GPP LTE respectively. [8] specifies a model estimating transient behavior of OFDMA system. All above works about OFDMA random access is an Aloha-type access in cellular network. In addition, [6] is one of a few works for 802.11. It generalizes CSMA/CA to OFDMA system for 802.11.

Though OFDMA and multi-channel random access have been employed by IEEE

802.16 and 3GPP LTE for a long time. It is the first time for 802.11ax to issue OFDMA and OFDMA-based random access, which is a huge evolution for 802.11. And as far as we know, this is the first paper analyzing IEEE 802.11ax OFDMA-based random access. It employs binary exponential backoff and MU PHY under Trigger-based MU UL, which is different from [6]. Since [2] proposes an accurate Markov chain model for DCF, we could also reuse this model to generate another Markov chain for 802.11ax to precisely depict the OFDMA-based random access. We assume stations are under saturated condition which means they always have packets to transmit. The saturated analysis is based on the key assumption of independent collision probability p whatever the packet is retransmitted or not. Simulation validates our model to be accurate. Then, we estimate the maximum system efficiency and minimum access delay. Since OFDMA-based random access has dynamic and more complicated parameter sets than legacy 802.11, we evaluate effect of a variety of parameter sets and at last propose rules for AP to configure the parameter set.

The paper is organized as follows. More explanations of 802.11ax features are given in section 2. In section 2.2, a detailed illustration of OFDMA-based random access procedure is presented. Section 3 contains the system model and performance analysis, including system efficiency and access delay, of the random access mechanism. Then section 3.3 shows simulation results compared with analysis results, which validates the model. In section 4.1, additional considerations on optimal performance are carried out. Section 4.2 gives performance evaluation under various parameter sets and at last propose rules for configuring the parameter set. Conclusion remark is given in section 5.

Chapter 2

802.11ax Features

The legacy random access is called distributed coordination function (DCF). Since the DCF degrades performance severely at dense scenario solution, IEEE 802.11ax proposes a centralized coordination, improving the status of AP. This centralized coordination function is also based on DCF so that 802.11ax is compatible with legacy 802.11 and other wireless system. At the same time, OFDMA is issued in IEEE 802.11ax to improve the system performance. In this section, we introduce MU PHY and TF-based MU UL.

2.1 Multi-User PHY

2.1.1 PHY

While legacy 802.11 specify a 20 MHz channel a Single User (SU) channel, which means only one user could access the channel at a time in a BSS, 802.11ax issues a flexible resource allocation based on OFDMA, allowing multiple STAs to access channel simultaneously. It should help mitigate contention and collision.

The resource unit (RU) in 802.11ax is more fine-grained, as specified in figure 2.1. The smallest RU is 26-tone, with which a 20 MHz could be separated into 9 subchannels. It is flexible that if there are not 9 HE-STAs to share the channel, AP could allocate multiple RUs to one HE-STA without wasting the RUs. And as specified in figure 2.1, multiple 20 MHz channels can be aggregated to be utilized by a BSS, which is called Channel Bonding.

RU type	CBW20	CBW40	CBW80	CBW80+80 and CBW160
26-tone RU(#838)	9	18	37	74
52-tone RU	4	8	16	32
106-tone RU	2	4	8	16
242-tone RU	1-SU/MU-MIMO	2	4	8
484-tone RU	N/A	1-SU/MU-MIMO	2	4
996-tone RU	N/A	N/A	1-SU/MU-MIMO	2
2×996 tone RU(#1337)	N/A	N/A	N/A	1-SU/MU-MIMO

Figure 2.1: Maximum number of RUs for each channel width

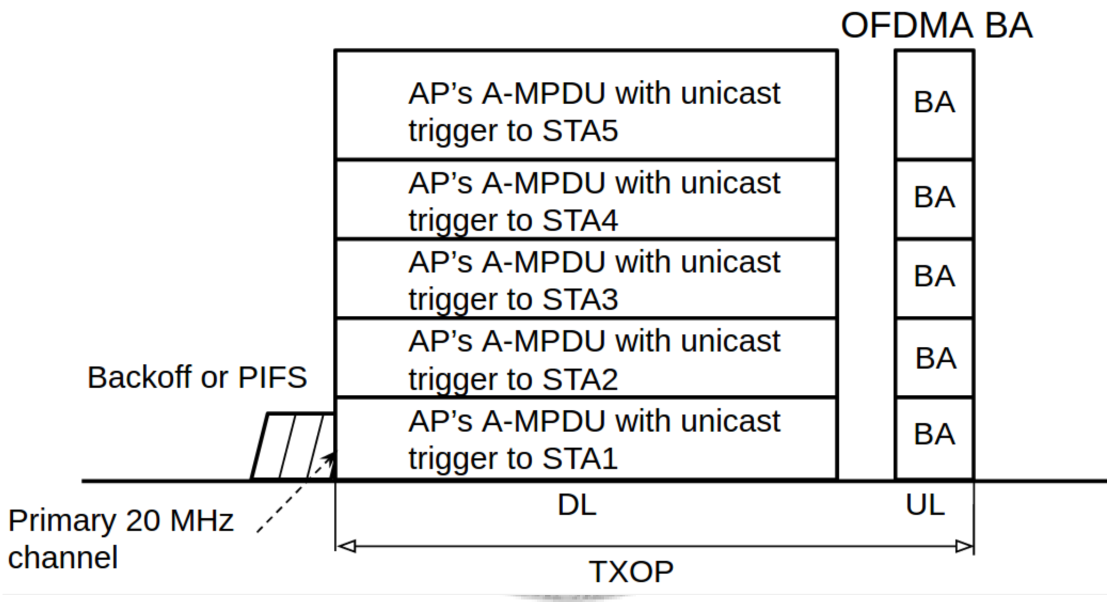

Figure 2.2: MU DL of 802.11ax

This will help a lot improve system performance, since one BSS is not restricted to a single 20 MHz channel. It is worth mentioning that every transmission of MU should end at the same time. That means padding is required for short packets.

Actually, MU PHY has been implemented in 802.11n and 802.11ac with MU-MIMO, which is an absolutely different method from OFDMA and beyond the scope of this paper.

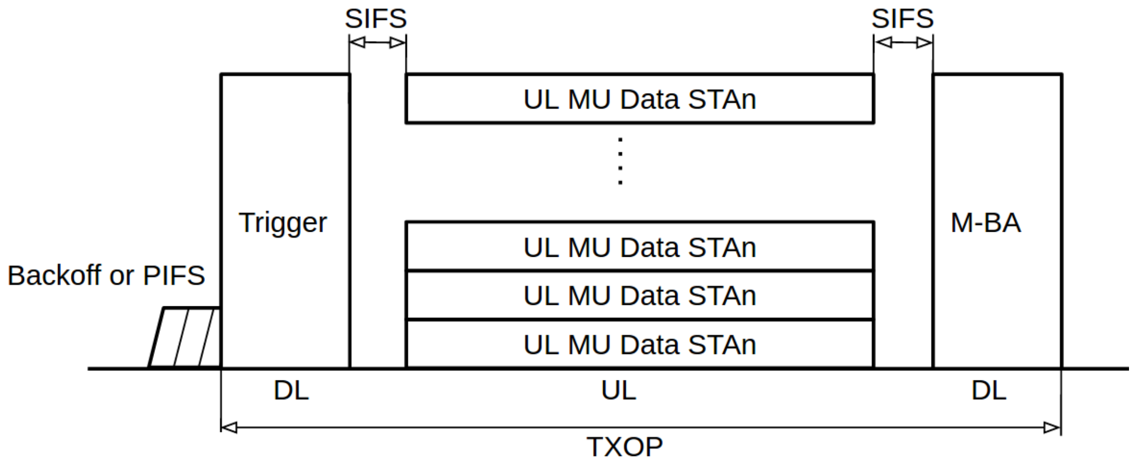

Figure 2.3: Trigger-based MU UL of 802.11ax

2.1.2 MAC

Since 802.11ax MAC is still based on DCF, AP will contend with DCF procedure to transmit DL packets with OFDMA to multiple stations, which is called MU DL as in figure 2.2. The difficulty of OFDMA MU is MU UL. 802.11 is not a synchronous system, preamble and even two-way handshaking are required before a data transmission. A trigger-based MU UL is issued as in figure 2.3. A brand new control frame, called trigger frame, is created to be transmitted by AP before HE-STAs transmitting a packet. In this way, stations is able to access channel with the scheduled RU contained in trigger frame transmitted by AP. The trigger frame format is as in figure 2.4. Since the standard is in progress, many fields remain to be determined (TBD).

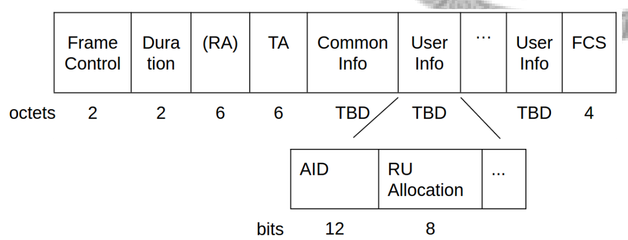

Figure 2.4: Trigger Frame format

The basic use of trigger frame is to allocate RUs. It contains resource allocation information in field user info, specifying some station to access some RU in subfield AID and RU allocation. When AP schedules RUs for random access, the subfield AID of User Info is set to value 0. The detailed procedure we will illustrate in section 2.2.

What's more, to support scheduling of TF, a mechanism called Target Wake Time (TWT) is implemented in 802.11ax. TWT is originally issued in 802.11ah for power saving[?]. It is also out of scope of this paper.

2.2 802.11ax Random Access Illustration

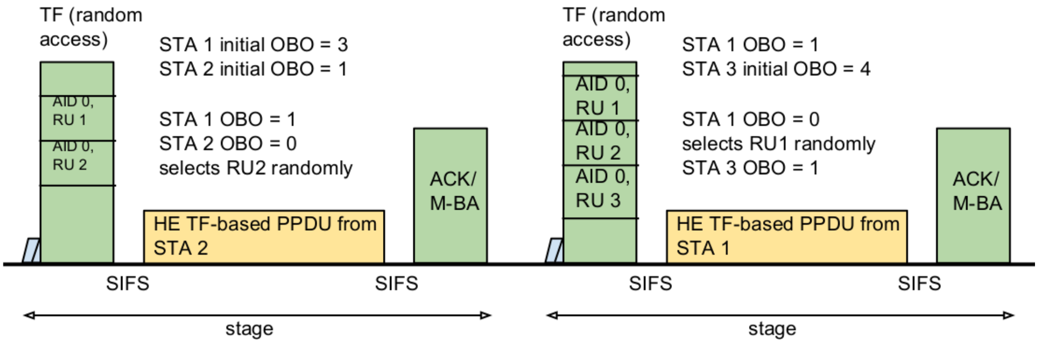

Figure 2.5: Illustration of OFDMA-based random access

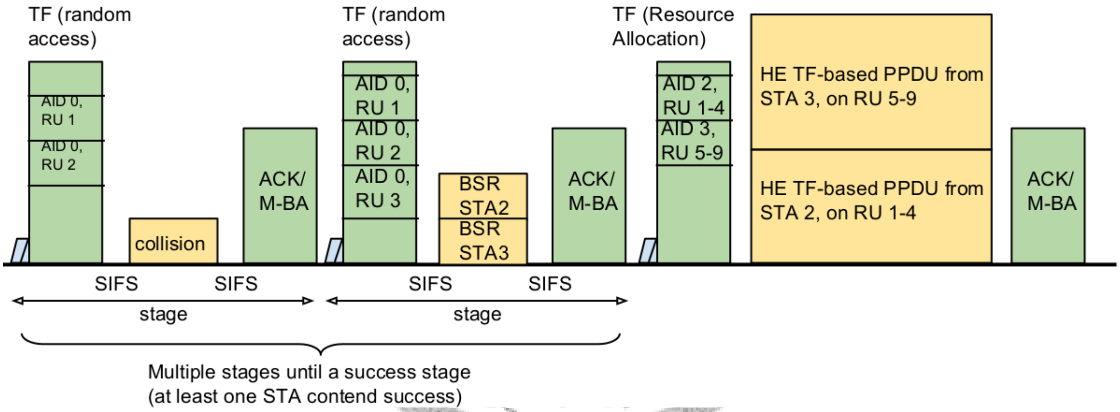

Figure 2.6: An example of OFDMA-based random access for UL in 802.11ax

As stated above, legacy IEEE 802.11 MAC is a 20MHz SU PHY, which means that at most single user could succeed in contending at a time slot. With the MU PHY, HE-STA (802.11ax, high efficient station) has multiple RUs to access, which means multiple HE-STAs may access channel at the same time. And the parameter set is set by AP in real time. The procedure is of course more complicated and flexible. We first illustrate the ODFMA-based random access procedure then give two use cases of the random access.

Different from legacy 802.11, all the parameters are configured by AP, not predefined at hardware. The parameter set is composed of OCW_{min}, OCW_{max}, M. OCW_{min}, (i.e., OFDMA contention window), represents the minimum contention window, while OCW_{max} represents the maximum contention window. And M is the number of RUs for random access. OCW_{min}, OCW_{max} are given in an element called RAPS (random access parameter set) contained in beacon frame sent by AP. In this way, HE-STA is able to access channel with different parameters obtained from the beacon frame.

In a beacon interval, to initialize a random access procedure, AP first transmits a trigger frame. The TF announces some RUs for random access by setting the AID of those RUs value of 0. HE-STA needs maintain a backoff counter, called OFDMA Backoff (OBO). HE-STAs who want to access channel will randomly generate a OBO among range $[0, OCW_i]$, where i is the backoff level. Then the OBO subtracts the value of number of RUs for random access in the current stage. If the OBO reaches 0, the HE-STA will randomly select a RU from those for random access to transmit a packet after SIFS (short inter-frame spacing). After that AP responds with a block ack indicating who succeed in transmitting a request. The whole three-way handshaking is called a stage. It is worth reminding that the stage in this paper is a concept of interval, not the backoff stage in other papers. It is specified from standard [1]. To distinguish the two words, we use backoff level replacing backoff stage. Those whose OBO is greater than 0 will freeze the OBO and wait for next stage. If more than one HE-STA transmit at the same RU, collision occurs. Those who collide in the current stage will double their OCW at next stage until OCW reaches OCW_{max}. Only if at least one HE-STA succeed in transmit a request in a stage will the stage be a successful stage.

Figure 2.5 illustrates the procedure. Green means transmission from AP to STA (i.e., DL) and yellow means UL direction. With clear illustration above, we look deeply into the implementation of the mechanism. See figure 2.7, the two critical parameters OCW_{min}, OCW_{max} are specified in field OCW Range. The value is defined by $OCW_{min} = 2^{EOCW_{min}} - 1$, $OCW_{max} = 2^{EOCW_{max}} - 1$. In the following analysis, we issue another parameter m, maximum backoff level, $OCW_{max} = (OCW_{min} + 1) * 2^m - 1$. So we specify OCW_{max} with m and OCW_{min} in following section, which helps analysis.

Following are two use cases of OFDMA-based random access. One is as figure 2.6

for UL random access. When HE-STA wants to random access to transmit data packets, he will send buffer state report (BSR) frame with OFDMA-based random access. After successful contention, AP will allocate RUs for the HE-STA by trigger frame.

Another use case of random access is for power save HE-STA to solicit buffered packets at AP, which is kind of DL transmission. Similar to legacy 802.11 power save, HE-STA needs to transmit PS-poll or APSD-trigger frame to inform AP of its active state when the HE-STA wakes up. The transmission of PS-poll or APSD-trigger frame is a good case of OFDMA-based random access. After successful contention, AP will transmit the buffered packets of the HE-STA.

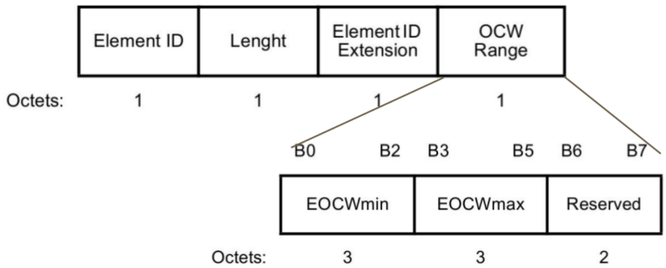

Figure 2.7: Random Access Parameter Set (RAPS) Element

Chapter 3

System Model

One of main contribution of this paper is the analytical evaluation of the saturation analysis of 802.11ax OFDMA-based random access, in the assumption of ideal channel conditions (i.e., no hidden terminals and capture). The Markov chain model of random access was first proposed by Bianchi for analyzing distributed coordination function[2]. Here, for the brand new ODFMA-based random access, we generate a new Markov chain model. In this analysis, we also generate three metrics, n_s number of stations who succeed in contending in a stage, eff self-defined system efficiency, and D access delay of request frame.

The analysis is divided into two parts. First is the Markov chain model to estimate the packet transmission probability τ and conditional collision probability p. Secondly, we express the three metrics as function of τ. Table 3.1 is a list of all parameters and notations.

Table 3.1: Parameters and Notations

n	# of stations
OCW_{min} or W_0	minimum OFDMA contention window
M	# of RUs for random access
m	maximum backoff level
p	packet collision probability
τ	station's transmission probability
n_s	# of successful stations in a stage
$N_{s\_station}$	# of stages for a station to succeed in contending
N_{s_stage}	# of stages until a successful stage

3.1 Packet Transmission Probability

Since 802.11ax implements OFDMA-MU and corresponding trigger-based UL, AP won't contend with 802.11ax stations under this situation. To estimate the performance of the OFDMA-based random access mechanism, we assume a saturated condition that each station always has packets to transmit as long as it accesses the channel. In the first use case, each station will contend to send Buffer Status Report (BSR), for convenience and easy understanding we call it request in the following context, for the data transmission later.

With above illustration of OFDMA-based random access mechanism, a 20 MHz channel, which is a single user (SU) channel in legacy 802.11, can be divided into 9 subchannels, called resource unit (RU). Consider a fixed number n of contending stations. M represents the number of RU for random access in a stage. W_i is the OFDMA contention window (OCW) at i^{th} backoff level, with relationship $W_i = 2W_{i-1} + 1$. Stations with OCW W_i will randomly generate a backoff counter among range $[0, W_i]$.

The bidimensional process $\{s(t), b(t)\}$, where $s(t)$ denotes the backoff level $(0, 1 \cdots, m)$ of a given station at time t and $b(t)$ denotes backoff time counter (i.e., OBO) for the station, will be modeled with Markov chain as in figure3.1. Since states $\{i, 0 \sim M\}$ all means station could access RU, we could merge these states into one state, denoted by $\{i, T\}$.

The model is based on the assumption that at each request transmission, and regardless of the number of retransmission suffered, each request frame collides with constant and independent probability p.

Let's assume $P\{i_1, k_1|i_0, k_0\} = P\{s(t+1) = i_1, b(t+1) = k_1|s(t) = i_0, b(t) = k_0\}$.

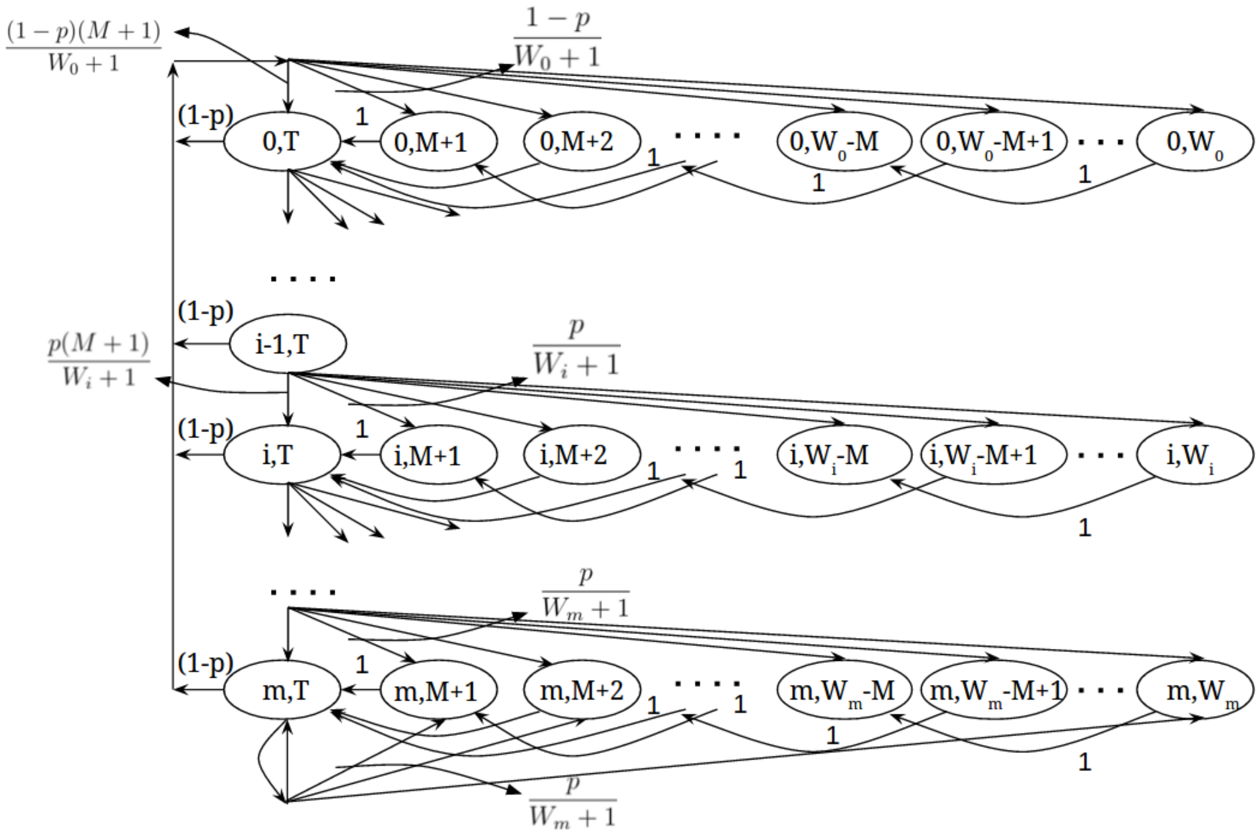

Figure 3.1: Markov Chain model for the backoff window size

In this Markov Chain, the only non null one-step transition probabilities are

$$\begin{cases} P\{i,T|i,k\} = 1 & k \in [M+1, 2M] \quad i \in [0,m] \\ P\{i,k-M|i,k\} = 1 & k \in [2M+1, W_i] \quad i \in [0,m] \\ P\{0,k|i,T\} = \frac{1-p}{W_0+1} & k \in [M+1, W_0] \quad i \in [0,m] \\ P\{0,T|i,T\} = \frac{(1-p)(M+1)}{W_0+1} & \quad i \in [0,m] \\ P\{i,k|i-1,T\} = \frac{p}{W_i+1} & k \in [M+1, W_i] \quad i \in [1,m] \\ P\{i,T|i-1,T\} = \frac{p(M+1)}{W_i+1} & \quad i \in [1,m] \\ P\{m,k|m,T\} = \frac{p}{W_m+1} & k \in [M+1, W_m] \\ P\{m,k|m,T\} = \frac{p(M+1)}{W_m+1} & \end{cases} \tag{3.1}$$

The first and second equations in 3.1 accounts for the fact that in a trigger frame stage for random access, the backoff counter maintained by stations will decrease the number of RUs for random access. The third and fourth equation represents that after a successful contention, stations will reset the contention window size to initial window size and uniformly generate a backoff value among $[0, W_0]$, since $T = [0, M]$, the transition probability to $\{i, T\}$ is $M + 1$ times of that to $\{i, k\}$. For the fifth and sixth equations, they represents when a failure contention occurs, the contention window size will be doubled. The last two equation is situation of failure contention at the maximum backoff level.

Let $b_{i,k} = \lim_{t\to\infty} P\{s(t) = i, b(t) = k\},\ i \in [0, m],\ k \in [0, W_i]$ be the stationary distribution of the Markov chain. Then we show the steady state for the Markov Chain. First, for $k = T$

$$b_{i-1,T} \cdot p = b_{i,T} \rightarrow b_{i,T} = p^i b_{0,T}, \quad 0 \le i < m \tag{3.2}$$

$$b_{m-1,T} \cdot p = (1-p) b_{m,T} \rightarrow b_{m,T} = \frac{p^m}{1-p} b_{0,T}. \tag{3.3}$$

Then,

$$b_{i,k} = \begin{cases} (\lfloor \frac{W_0-k}{M} \rfloor + 1) \frac{(1-p)}{W_0+1} \sum_{i=0}^{m} b_{i,T}, & M+1 \le k \le W_0,\ i = 0 \\ (\lfloor \frac{W_i-k}{M} \rfloor + 1) \frac{p}{W_i+1} b_{i-1,T}, & M+1 \le k \le W_i,\ 0 < i < m \\ (\lfloor \frac{W_m-k}{M} \rfloor + 1) \frac{p}{W_m+1} (b_{m-1,T} + b_{m,T}), & M+1 \le k \le W_m, \quad i = m \end{cases} \tag{3.4}$$

From equation 3.3, we have $\sum_{i=0}^{m} b_{i,T} = \frac{b_{0,T}}{1-p}$; sum the equation 3.4 respectively, we obtain equation 3.5.

$$\begin{cases} \sum_{k=M+1}^{W_0} b_{0,k} = \frac{b_{0,T}}{W_0+1} \left(-\frac{M}{2} \left\lfloor \frac{W_0}{M} \right\rfloor^2 + \left(W_0 - \frac{M}{2} \right) \left\lfloor \frac{W_0}{M} \right\rfloor \right) \\ \sum_{i=1}^{m-1} \sum_{k=M+1}^{W_i} b_{i,k} = \frac{b_{0,T}}{W_0+1} \left(\frac{p}{2} \right)^i \left(-\frac{M}{2} \left\lfloor \frac{W_i}{M} \right\rfloor^2 + \left(W_i - \frac{M}{2} \right) \left\lfloor \frac{W_i}{M} \right\rfloor \right) \\ \sum_{k=M+1}^{W_m} b_{m,k} = \frac{b_{0,T}}{W_0+1} \frac{(\frac{p}{2})^m}{1-p} \left(-\frac{M}{2} \left\lfloor \frac{W_m}{M} \right\rfloor^2 + \left(W_m - \frac{M}{2} \right) \left\lfloor \frac{W_m}{M} \right\rfloor \right) \end{cases} \tag{3.5}$$

Let $X_i = -\frac{M}{2}\left\lfloor\frac{W_i}{M}\right\rfloor^2 + \left(W_i - \frac{M}{2}\right)\left\lfloor\frac{W_i}{M}\right\rfloor$. Then we sum all the states to have equation 3.7.

We can now express τ, the probability of a station transmit a request at a randomly selected stage.

$$\tau = \sum_{i=0}^{m} b_{i,T} = \frac{b_{0,T}}{1-p} = \frac{W_0+1}{W_0+1+(1-p)X_0+(1-p)\sum_{i=1}^{m-1} X_i\left(\frac{p}{2}\right)^i + X_m\left(\frac{p}{2}\right)^m} \tag{3.8}$$

For $m = 0$, check equation 3.6, the terms containing $X_i, i > 0$ will disappear, and $b_{0,T}/(1-p)$ will just be $b_{0,T}$. Thus, equation 3.7 will be simplified to

$$1 = b_{0,T}\left(\frac{W_0+1+X_0}{W_0+1}\right), \tag{3.9}$$

thereby,

$$\tau = b_{0,T} = \frac{W_0+1}{W_0+1+X_0}. \tag{3.10}$$

Thus τ is independent with n, number of contending stations.

On the other hand, conditional collision probability p is the probability that no other stations select the same RU to transmit request. So we have

$$p = 1 - \left(1 - \frac{\tau}{M}\right)^{n-1}. \tag{3.11}$$

Rewrite the equation 3.11, $\tau^{\star} = \left(1-(1-p)^{\frac{1}{n-1}}\right)M$. To obtain transmission probability

$$1 = \sum_{i=0}^{m}\sum_{k=0}^{W_i} b_{i,k} = \frac{b_{0,T}}{W_0+1}\left(X_0 + \sum_{i=1}^{m-1} X_i\left(\frac{p}{2}\right)^i + X_m\frac{\left(\frac{p}{2}\right)^m}{1-p}\right) + \frac{b_{0,T}}{1-p} \tag{3.6}$$

$$= b_{0,T}\left(\frac{(1-p)X_0+(1-p)\sum_{i=1}^{m-1} X_i\left(\frac{p}{2}\right)^i + X_m\left(\frac{p}{2}\right)^m + W_0+1}{(W_0+1)(1-p)}\right) \tag{3.7}$$

τ and conditional probability p, we need to find solutions to group of equations 3.8 and 3.11. $\tau^{\star}(p)$ is a monotonically increasing function. Though $\tau(p)$ is hard to determine the monotonicity from the expression of equation 3.8 with respect to p. We justify the monotonic decrease of function 3.8 with numerical method. Also, $\tau(0) = \frac{W_0+1}{W_0+1+X_0} > \tau^{\star}(0) = 0$. And $\tau(1) < \tau^{\star}(1) = M$. We find the only solution with numerical method.

3.2 Random Access Efficiency

With the transmit probability, we could easily estimate efficiency of random access mechanism. Firstly, find expected number of stations who succeed in contending to transmit request at a stage, which is denoted with $E[n_s]$. Extending n_s, we define a system efficiency as an important metric. Secondly, we are interested in the access delay of request frame. In another word, say how many stages needed for a station to succeed in contending, denoted by $N_{s\_station}$. What's more, another interesting metric is how many stages are elapsed until a successful stage, which means at least one station succeed in contending in the stage. This metric is a concept similar to "delay" in the second use case of OFDMA-based random access. We represent it with N_{s_stage}. It helps design whole MU UL transmission procedure. Here, our concern is mainly on first two metrics which are purely related to random access procedure. The third metric is only expressed in the subsection of access delay, not being discussed later.

3.2.1 n_s and System Efficiency

What we care in the random access is that how many stations contend successfully in a single stage, denoted by n_s. Given transmission probability τ and conditional collision probability p, we could obtain probability that a station succeeds in contending in a stage,

$P_{s\_station} = \tau(1-p)$. Then, with equation 3.11, $E[n_s]$ is easily computed as follows.

$$\begin{aligned} E[n_s] &= nP_{s\_station} \\ &= n\tau(1-p) \\ &= n\tau(1-\frac{\tau}{M})^{n-1} \end{aligned} \tag{3.12}$$

Furthermore, normalizing n_s, system efficiency here is defined as

$$\begin{aligned} \text{eff}\,(\tau) &= \frac{E[\text{number of successful stations in a given stage}]}{\text{number of RUs for random access in a stgae}} \\ &= \frac{E[n_s]}{M} \\ &= \frac{n\tau(1-\frac{\tau}{M})^{n-1}}{M}. \end{aligned} \tag{3.13}$$

Both two metrics are our concerns. Another metric, access delay, is derived in next subsection. With all these metrics, we could evaluate the performance later.

3.2.2 Access Delay

$N_{s\_station}$, the random variable of how many stages are needed for a station to succeed in contending in a stage follows geometric distribution with parameter $P_{s\_station}$, which is obtained just now. Then the expected value of access delay of request frame, $E[D]$, is

$$E[D] = E[N_{s\_station}] = \frac{1}{\tau(1-\frac{\tau}{M})^{n-1}}. \tag{3.14}$$

Then another interesting metric which is not our focus, denoted by N_{s_stage}, that how many stages are elapsed until a successful stage. We could firstly obtain P_{s_stage}, the probability of a successful stage, which means at least one station succeed in contending in the stage.

$$\begin{aligned} P_{s\_stage} &= 1 - P\{n_s = 0\} \\ &= 1 - (1 - P_{s\_station})^n \\ &= 1 - (1 - \tau(1-p))^n \end{aligned} \tag{3.15}$$

Since N_{s_stage} follows geometric distribution with parameter P_{s_stage},

$$\begin{aligned} E[N_{s\_stage}] &= \frac{1}{P_{s\_stage}} \\ &= \frac{1}{1 - (1 - \tau(1-p))^n} \end{aligned} \tag{3.16}$$

In a word, we focus on three metrics: number of successful stations in a stage by n_s, system efficiency by $E[n_s]/M$ and access delay given by $N_{s\_station}$. Actually, only two variables are concerned, n_s and $N_{s\_station}$. However, n_s and its normalized value are both meaningful, which we will explain in following sections.

3.3 Model Validation

To validate the Markov chain model, we run a simulation using C language according to the settings of 802.11ax random access illustration. We run the simulation with variety of parameter sets $\{M, m, OCW_{min}\}$ and collects the information of the two variables, n_s and $N_{s\_station}$. The validation is given in both figure 3.2 and table 3.2. The results show that the Markov model precisely predict the behavior of the OFDMA-based random access.

Table 3.2: Analysis versus simulation: n_s and access delay with $m = 3, M = 9, OCW_{min} = 15$

n_s	analysis	simulation
$n = 1$	0.72727	0.72728
$n = 5$	2.23001	2.22335
$n = 10$	2.88954	2.88546
$n = 20$	3.29798	3.29857
delay	analysis	simulation
$n = 1$	1.37500	1.37499
$n = 5$	2.24214	2.24886
$n = 10$	3.46075	3.46565
$n = 20$	6.06432	6.06323

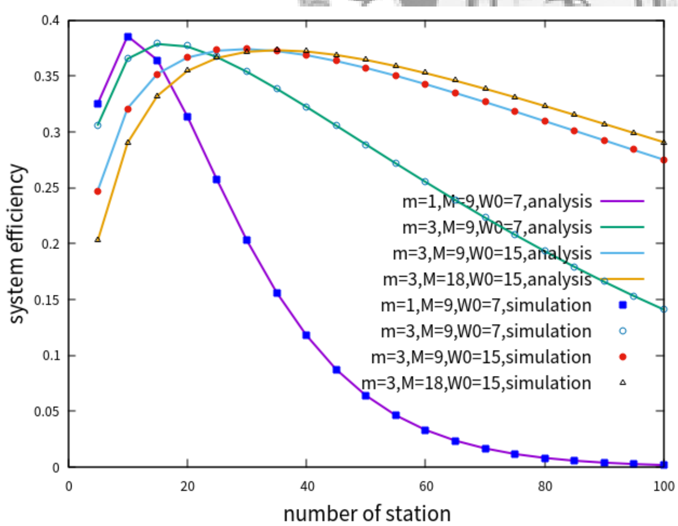

Figure 3.2: System efficiency: Analysis versus Simulation

Chapter 4

Performance Evaluation

4.1 Maximum System Efficiency and Minimum Access Delay

With the system efficiency given in equation 3.13, we take the derivative with respect to τ, and find the extreme point, $\tau^\star = M/n$. Since $\tau \in [0, 1]$, $\tau^\star = min\{1, M/n\}$. What we care is when n, the number of contending stations, is large, i.e., $\tau^\star = M/n$. Then the system efficiency is

$$\text{eff}\,(\tau^\star) = (1 - \frac{1}{n})^{n-1} \tag{4.1}$$

Then the maximum n_s is easy to generate.

$$E[n_s]^\star = M \cdot \text{eff}\,(\tau^\star) = M(1 - \frac{1}{n})^{n-1} \tag{4.2}$$

And the limit on n is

$$\lim_{n\to\infty} \text{eff}\,(\tau^\star) = \lim_{n\to\infty} (1 - \frac{1}{n})^{n-1} = \frac{1}{e} \tag{4.3}$$

With the delay analysis given in 3.14, we also take the derivative with respect to τ, and find the extreme point, $\tau^\star = M/n$. Again, $\tau^\star = min\{1, M/n\}$. When $n \geq M$, the

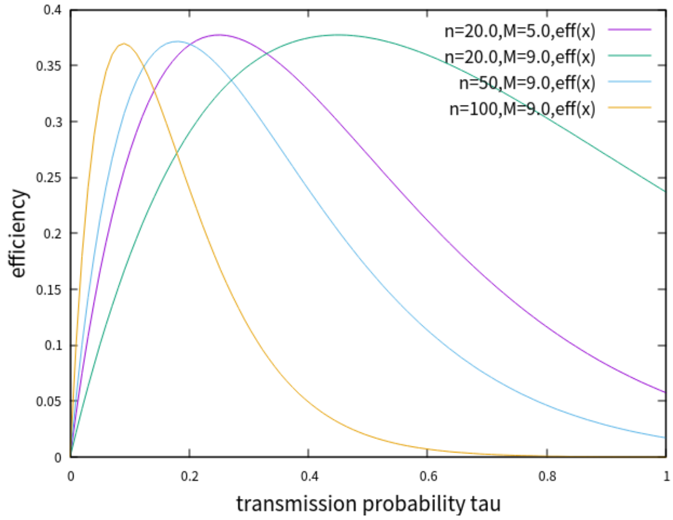

Figure 4.1: Efficiency versus transmission probability τ

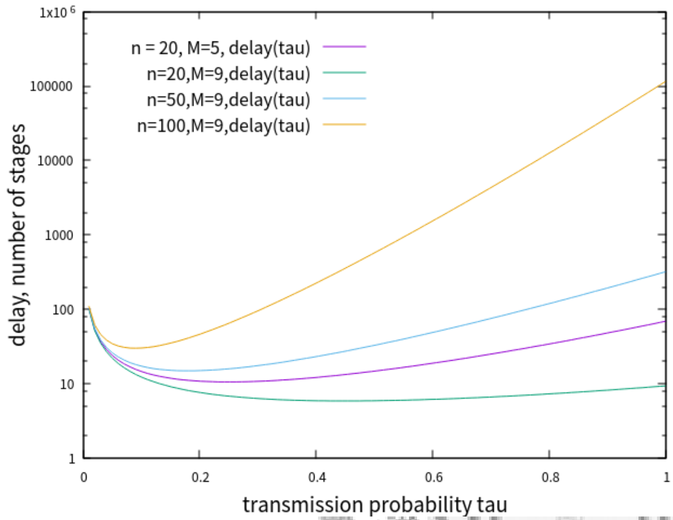

Figure 4.2: Access delay versus transmission probability τ

minimum access delay is

$$D(\tau^{\star}) = \frac{n}{M(1-\frac{1}{n})^{n-1}}. \tag{4.4}$$

From above analysis, we find that the maximum system efficiency and minimum access delay are both obtained by the same transmission probability $\tau = min\{1, M/n\}$. What's more, system efficiency is independent with M, number of RUs for random access in a stage, while M affects access delay. The larger M is, the shorter the access delay will be. It indicates that when AP allocates RUs for random access, the AP could allocates as many as possible, only if the channel of the RU is sensed idle. This rule will be more explained in next section.

Figure 4.1 and figure 4.2 are plotted corresponding to equation 3.13 and 3.14 respectively. Consistent to the analysis above, the figure shows that the maximum system efficiency is independent of number of RUs for random access when $n \geq M$, and approaching to $1/e$ with n increasing. What's more, the optimal transmission probability τ of system efficiency and access delay is consistent with each other, which also validates the analysis.

According to equation 3.8 and 3.11, transmission probability τ is dependent on system parameters, m, backoff levels, M, RUs for random access in a stage, W_0, the initial contention window and n, number of stations in the network. The only way to approach optimal performance is to employ adaptive techniques to tune the values m, M and W on the basis of the estimated value of n. In the following section, we will evaluate the performance corresponding to different system parameters sets and propose the rules to tune the system parameter sets so that the transmission probability τ approach the optimal transmission probability, $\tau^{\star}$, which means both system efficiency and delay approach the optimal.

4.2 Rules of Parameter Configuration

We have estimated the maximum system efficiency and minimum access delay in the previous section. Then we evaluate the metrics, number of stations who succeed in contending in a stage, system efficiency and access delay, under various parameter sets. Equally, we could evaluates transmission probability under various parameter sets, since the optimal transmission probability $\tau^{\star}$ means both maximum system efficiency and minimal access delay.

At last, we propose rules for configuring the parameter set $\{M, m, OCW_{min}\}$.

4.2.1 RUs for Random Access M

The analysis above has indicated that M, the number of RUs for random access, only affects the minimum access delay, having nothing to do with maximum system efficiency.

And the bigger M is, the better the performance will be. We will give more explanations here.

In figure 4.3, the maximum system efficiency is almost the same. The difference is "when" the optimal point will be. For larger M, the optimal number of stations is larger. It is intuitive.

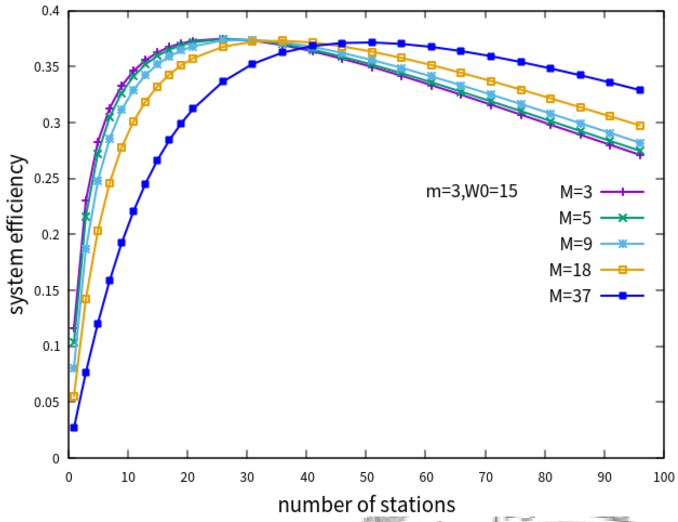

Figure 4.3: System efficiency versus number of stations

In figure 4.4, the larger M will linearly decrease the access delay of station. The figure is consistent with the equation 4.4.

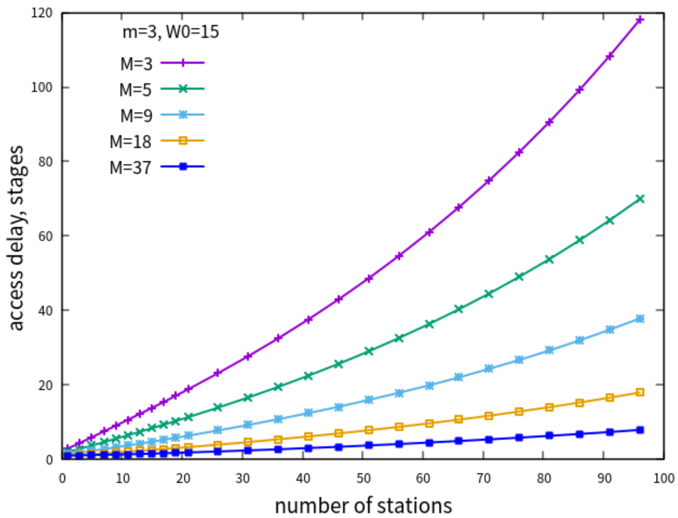

Figure 4.4: Access delay versus number of stations

More practically, we present the number of successful stations in a single stage versus number of stations in figure 4.5. While the maximum system efficiency is the same with different M, the actually number of stations who succeed contending in a single stage is much different, which corresponds to equation 4.2. The optimal value of number of successful stations in a single stage is propotional to M. Above all, when AP allocates RUs for random access, the AP will sense channels first then allocates as many RUs, which are sensed idle, for random access as possible.

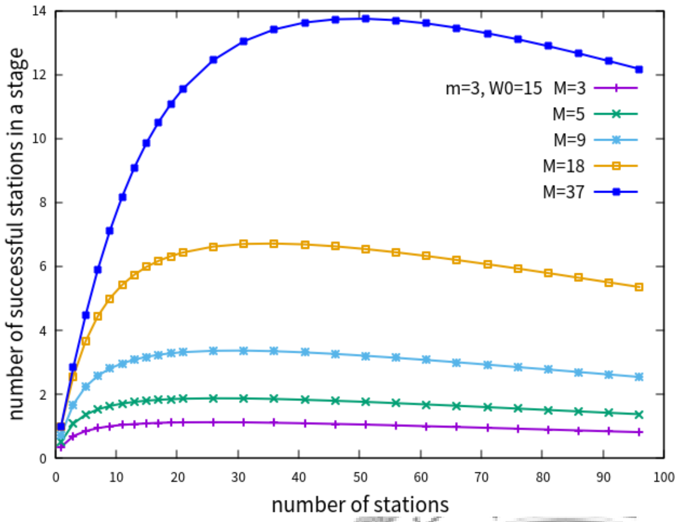

Figure 4.5: Number of successful stations in a single stage versus number of stations

4.2.2 Initial Contention Window OCW_{min}, backoff level m

Different from legacy 802.11, the backoff level and initial contention window are allocated as a RAPS element in beacon frame by AP in real time according to the system state, especially number of stations in a BSS. With the M being determined as large as possible, we need an adaptive tuning of backoff level and initial contention window so that transmission probability approaches optimal value. Since τ is determined by solving equations 3.8 and 3.11, it is hard to give a equation of τ determined by system parameters m and W_0. However, we could find the rules by checking a variety of parameter sets.

Refer to figure 4.6, the red line without point is the optimal τ with $M = 9$, which is given according to $\tau^{\star} = min\{1, M/n\}$. As stated above, we need to find a tuning of m and OCW_{min} so that τ approaches the optimal line.

The OCW_{min}, namely W_0, determines the start of the line of τ. The larger W_0 is, the lower transmission probability will start at $n = 1$. That's why cases in figure 4.6 have three different start points, which are corresponding to $W_0 = 7, 15, 31$ respectively. When $n \leq M$, $\tau^{\star} = 1$. Thus, when n is small, smaller OCW_{min} is preferred. What's more, a special case of $m = 0$ results in constant transmission probability which is perfect match with $\tau^{\star}$. Thus, if given $n \leq M$, the optimal configuration will be $m = 0, OCW_{min} = 7$. Since $M \geq 9$ is obvious under the rule of configuration of M, $OCW_{min} < 7$ equals to effect of $OCW_{min} = 7$. It is reasonable that we assume that minimum of OCW_{min} is 7.

Since the value of W_0 is given by $OCW_{min} = 2^{EOCW_{min}} - 1$, the expected values of contention window is not continuous. A sequence values, $7, 15, 31$, are thus given by configuring $EOCW_{min} = 3, 4, 5$.

To estimate the influence of backoff level, which equals to the effect of OCW_{max}, we give various values of m as in the figure 4.6. When $m = 0$, τ will not change with n, which is consistent with equation 3.10. For those $m > 0$, the curve will be convex. It is intuitive that with the number of stations increasing, the collision probability will increase, thus contention window increase. Thereby it results in decrease of transmission probability. And larger m is more fit to optimal transmission probability when n is large. It is validated by the case $m = 3, W_0 = 31$ in figure 4.7 that when $n > 30$, the system efficiency is much better than other cases.

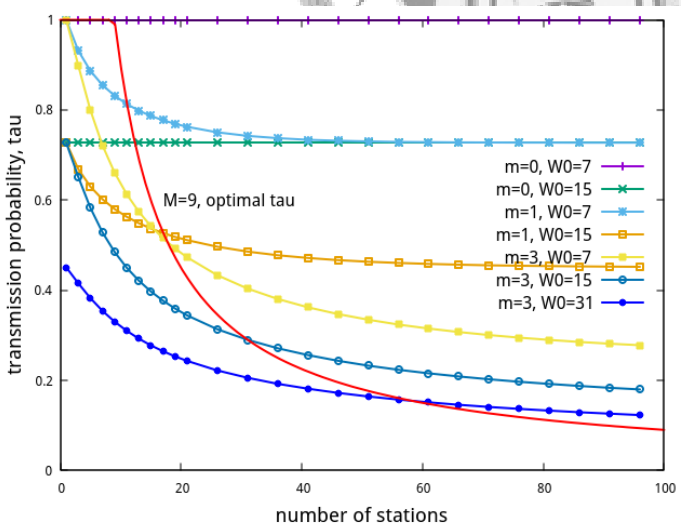

Figure 4.6: Transmission probability versus number of stations

Then, we check the system efficiency and access delay under different parameter sets of $\{m, W_0\}$. They validate all the rules stated above. Firstly, optimal performance is reached under the same system state, i.e. the same m, W_0 and the same n. Secondly, smaller OCW_{min} has better performance when n is small. Thirdly, larger m, which means larger OCW_{max}, has better performance when n is large.

Let's take two extreme examples. With smaller m and OCW_{min}, performance is pretty well but degrades a lot when n gets larger, While with larger m and OCW_{min}, performance is pretty at large n but much worse for small n. To obtain best performance for $n > M$, we propose to adaptively tune the parameter sets $\{m, OCW_{min}\}$ with large m and small OCW_{min} together with M as large as possible.

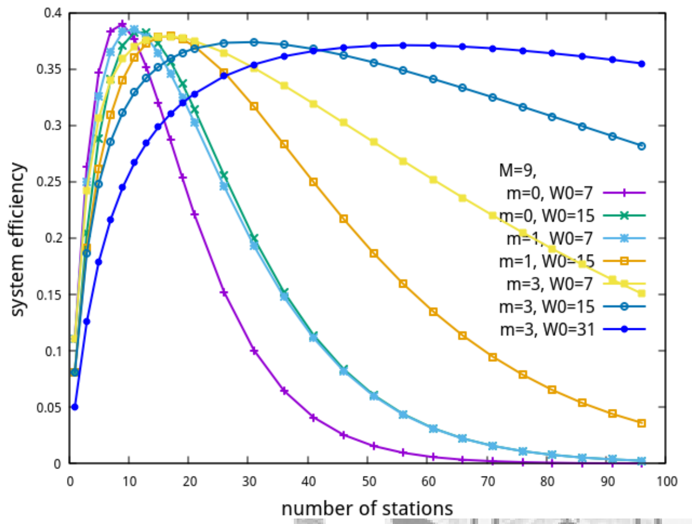

Figure 4.7: System efficiency versus number of stations

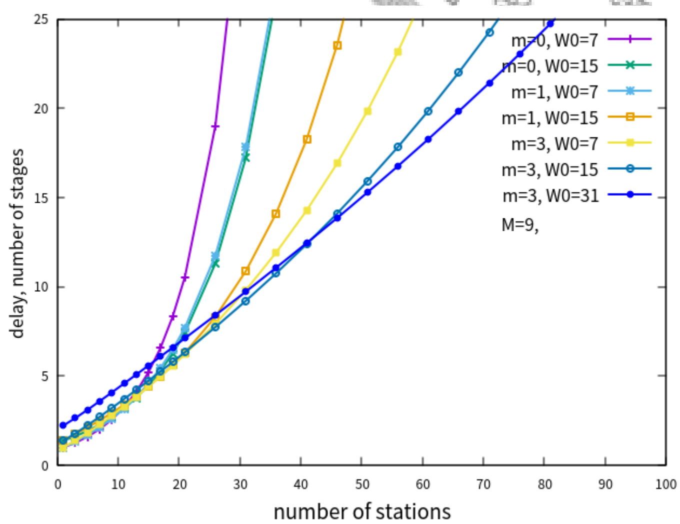

Figure 4.8: Access delay versus number of stations

4.2.3 Rules for configuring $\{M, m, OCW_{min}\}$

Above two previous subsections, we could conclude rules of configuring the parameter set $\{M, m, OCW_{min}\}$ for obtaining best performance for all n.

- M, as large as possible for all n.
- m, OCW_{min}
  - $n \leq M$, $m = 0$ and small OCW_{min}
  - $n > M$, large m and small OCW_{min}

After we propose the rules of configuring the parameter set $\{M, m, OCW_{min}\}$, we run another analysis with typical group parameter sets which validate our rules.

From figure 4.10, larger $M = 18$ results in larger n_s, number of successful stations in a single stage, than $M = 9$. Thus, M is as large as possible. Then given a $M = 18$ as an example, smaller $W_0 = 7$ and larger $m = 7$ have better performance than other parameter sets when $n > M$.

For the system state that $n \leq M$, n_s and access delay of $m = 0, W_0 = 7$ is the best case among all the parameter sets. It is because the transmission probability under such condition reaches the optimal value as in figure 4.6.

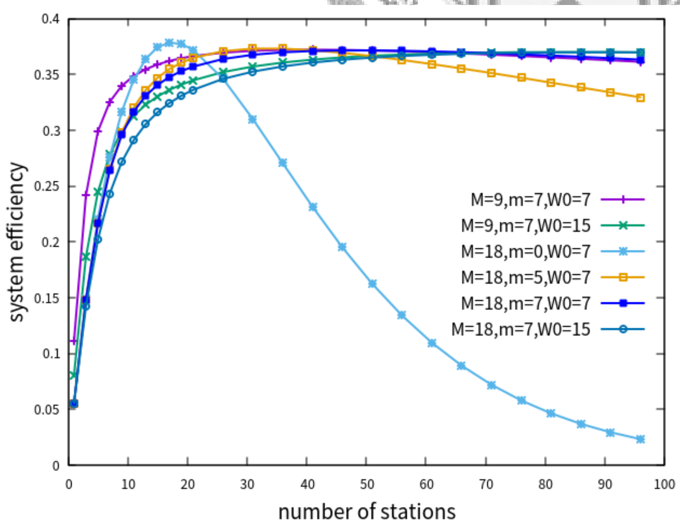

Figure 4.9: System efficiency versus number of stations

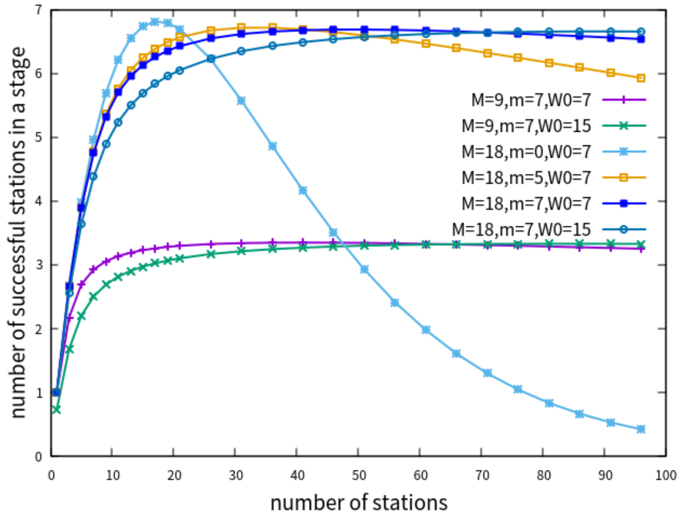

Figure 4.10: n_s versus number of stations

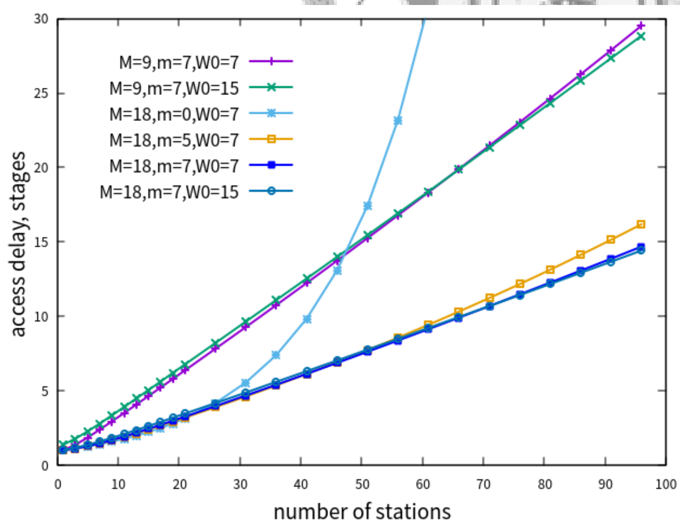

Figure 4.11: Access Delay versus number of stations

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Chapter 5

Conclusion

In this paper, we illustrate one of important features of the IEEE 802.11ax MAC, OFDMA-based random access. Different from legacy 802.11, the OFDMA-based random access mechanism is more complicated and flexible, not only multiple channels being allocated for random access, but also the parameter set being configured by AP in real time. We generate a new Markov chain model of the OFDMA-based random access and validate our model by simulation.

With the model, we derive the maximum system efficiency and minimum access delay, and estimate the effect of a parameter set $\{M, m, OCW_{min}\}$ on system efficiency and access delay, where M is the number of RUs for random access, m is the maximum backoff levels, and OCW_{min} is the initial OFDMA contention window. All the three parameters have great impact on performance. An interesting result is that the maximum system efficiency and minimum access delay are obtained by the same transmission probability τ, which is given by $\tau^{\star} = min\{1, M/n\}$. Then rules of configuration of parameter set aimed at reaching the optimal transmission probability $\tau^{\star}$ is proposed for AP according to system state, mainly the number of contending stations. The last group cases of various parameter sets validates our proposed rules.

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