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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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所　長：

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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 devices or users and exploding traffic, the WLAN is more and more dense. Gradually, problem from the instability of distributed coordination function (DCF), which is the foundation of legacy 802.11 MAC, has arisen. That is, severe collision causes degradation of throughput, defer access, and waste energy of stations. Thus, task group IEEE 802.11ax, which was set up in 2014 confronting the above problem, makes revolutionary 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 thesis extends bi-dimensional discrete-time Markov Chain to model the OFDMA-based random access, which accurately depicts its steady state behavior. With this model, we also 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. However, problems arise with more and more dense deployment of WiFi. Though the throughput of WiFi has increased to x Gbit/s, the quality of experience (QoE) is not improved with the throughput. That is because the bottleneck is located at MAC, distributed coordination function (DCF), which is the foundation of 802.11 MAC. DCF is a random access mechanism. Details of DCF could be referred to [4].

With tremendous increase of WiFi deployment, there are more and more basic service sets (BSS) overlapping with each other and each BSS has more and more devices, which will cause severe interference. According to Cisco Visual Network index[7], the mobile traffic will increase 53% at CAGR within 2015-2020, which means increase eightfold during the 5 years. What's more, other systems, like 3GPP, also engage in WLAN in the unlicensed band called LTE-U. WLAN in the unlicensed band will become more and more dense. Thus, supporting such a dense deployment remains critical to be solved.

1.1 Defects of Legacy 802.11

As stated above that the bottleneck is located at MAC. It is not efficient under dense scenario. In this section, we would display clearly about two inherent defects of legacy 802.11 MAC, including instability of DCF and unfair queueing problem.

Instability of DCF

Refer to Bianchi's saturated analysis of DCF[4], the throughput degrades sharply with the number of stations increasing as in figure 1.1. We could extend Bianchi's analysis to obtain the energy performance. Stations have roughly three working states, ”transmit”, ”receive” and ”idle”. Check the figure 1.2, with the number of stations increases, the partition of time working in transmit state for each station decreases a lot while partition in receive state increases much. That means a station has much less chance to transmit. And with the decrease throughput, we could know that most of transmissions are collided with others. Then let's look at the energy performance by checking the figure 1.3. We find that total energy consumption of a station increase a lot while successful transmissions are less. Most of energy are wasted on listening to collided transmissions. We thus could conclude that the DCF is inherently unstable and is not fit for dense scenario.

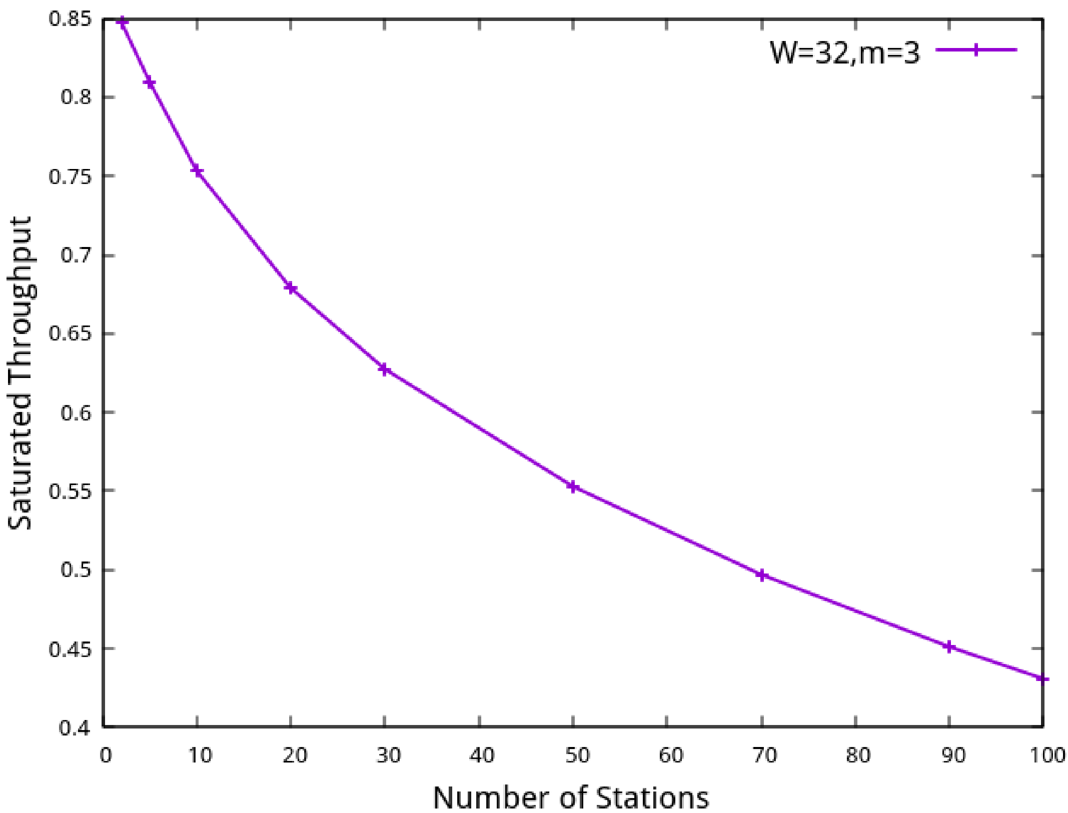


Figure 1.1: Saturated analysis: throughput vs number of stations

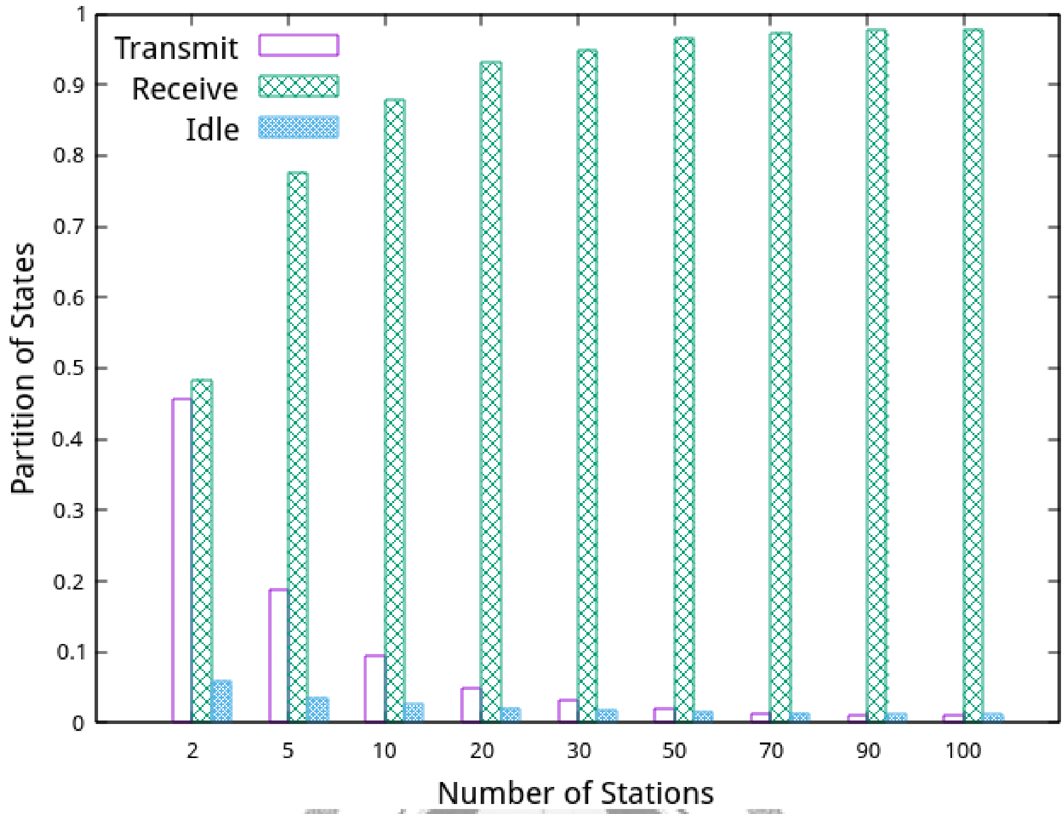


Figure 1.2: Partition of working states of a station under saturated condition

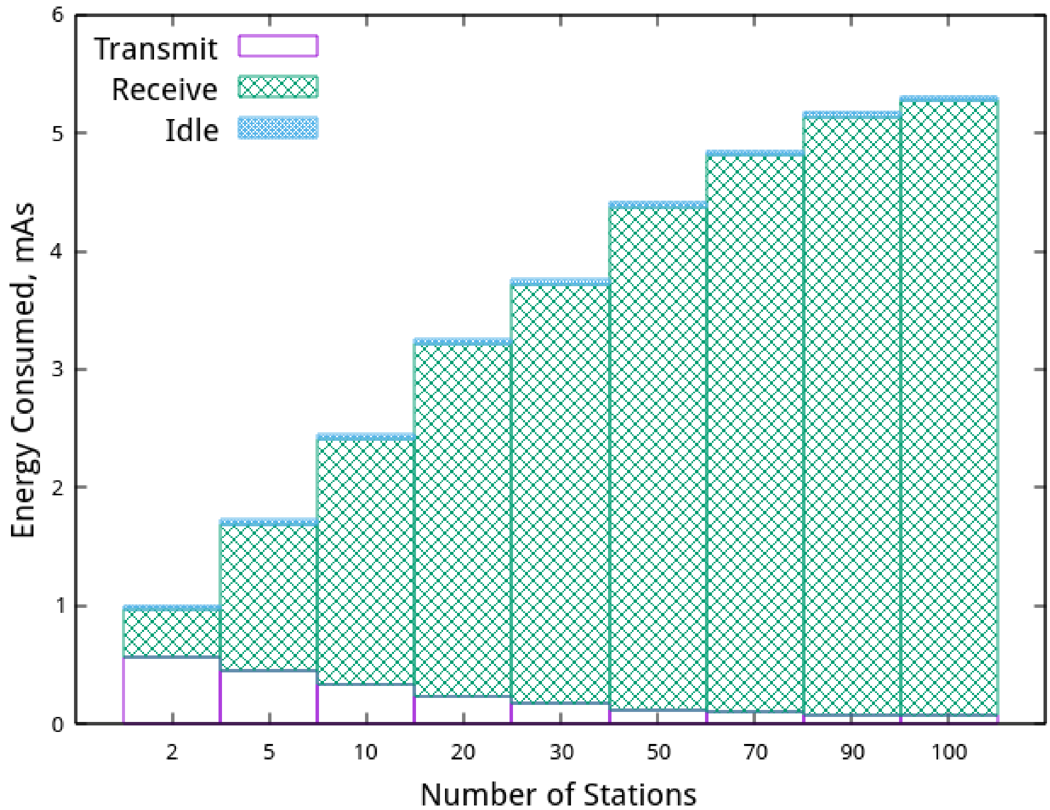


Figure 1.3: Energy consumption of a station under saturated condition

Unfair Queueing Problem

DCF together with the star topology of a BSS results in a absolutely unfair queueing. Check the figure 1.4. When we see the BSS with queue model, each station will be a queue, including AP. And channel is the server, which serve packets from stations. Channel capacity determines the serve rate. Since BSS is star topology, access point (AP) needs to transmit all the down-link (DL) traffic, which means AP shares more than 1/2 traffic loading of a BSS. However, since DCF is a distributed random access mechanism, AP has only $1/n$ chance to access medium where n is the number of total stations including AP. It is, thus, an unfair queueing problem for up-link (UL) and DL transmission. This problem may not result bad consequence only if the "server" is fast enough. That's what a list of previous amendments, like 802.11n and ac, were doing, improving throughput from 2 Mbit/s to 7 Gbit/s. However, this solution doesn't resolve the unfair queueing inherently. The unfair queueing is always there only if each station access channel with DCF. Once the BSS becomes congested the unfair queueing will worsen the effect of instability of DCF, resulting in more waste of spectrum and energy.

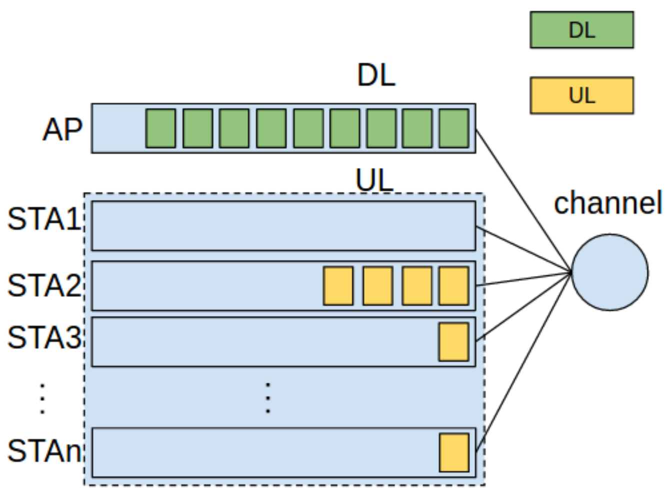


Figure 1.4: Unfair queueing problem of BSS

1.2 Solution: 802.11ax

Previous amendments, 802.11n and 802.11ac called high throughput (HT) and very high throughput (VHT) respectively, mainly focus on modifying PHY layer to improve throughput[14]. However, this throughput is estimated under ideal condition, while the real world suffers a lot from instability of DCF and unfair queueing problem under dense scenario. That's why the QoE doesn't improve with the throughput. Actually, the bottleneck is located at the MAC layer. Thus, 802.11ax task group is issued targeted at High Efficiency WLAN (HEW)[2], which make revolutionary modification to both MAC and PHY layers. Only in this way, quality of experience (QoE) could be improved and energy consumption could be reduced significantly. IEEE 802.11ax also proposes new metrics to measure the performance such as average throughput per station rather than total throughput. Various "dense scenarios" defined in document [16] will be used to measure the performance of 802.11ax. Confronting the dense deployment scenario, 802.11ax permits AP as central controller to schedule both DL and UL transmission. In this way, 802.11ax's MAC will not be a distributed random access mechanism and unfair queueing problem could be resolved inherently. IEEE 802.11ax also issues multi-user (MU) PHY, which is implemented with Orthogonal Frequency Multiple Access (OFDMA) or MU-MIMO, to improve efficiency. MU-MIMO is beyond this thesis. Though 802.11ax could have a scheduled MAC, random access is still high efficient in unpredictable data transmission. Thus, a multi-channel random access is also proposed in the 802.11ax standard draft [1]. They could be an efficient way for stations to initialize a traffic stream by sending bandwidth request.

To support OFDMA UL transmission and the OFDMA-based random access, a special control frame, trigger frame (TF), is created to implement trigger-based MU UL[1]. 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 scheduled by AP. Detailed illustration of 802.11ax MAC MU feature is in chapter 2.

The OFDMA-based random access is the focus of this paper. In the following chapters, we assume a saturated condition, which means stations always have packets to transmit. Under such assumption, we will extend Bianchi's Markov Model to model the Aloha-like OFDMA-based random access so that we could evaluate the steady state behavior of the mechanism. At last, we propose a list of rules of configuring system parameters based on the model analysis.

1.3 Related Work

Random access is one approach of multiaccess sharing in data network. Inherently, collision resolution algorithms can achieve small delay with a large number of lightly loaded nodes, the stability is a major concern[3][5]. Random access originates from Aloha and slotted Aloha in single-user channel. Then CSMA works as typical collision resolution [12], which is modified and then accepted by IEEE 802.11, named CSMA/CA. The backoff mechanism determines the way of retransmission when failure occurs. Binary exponential backoff is one of typical backoff mechanism, which has been applied by 802.11 until now. 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 MU channel, randomness extends from time domain to time-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. [6] designs a 1-persistent type retransmission, i.e., no exponential backoff, to achieve a fast access. In [18], 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, like [18] [15] [11]. The two backoff mechanisms are implemented by IEEE 802.16 and 3GPP LTE respectively. [17] 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, [13] is one of few works for 802.11 WLAN. It generalizes CSMA/CA to OFDMA system for 802.11.

1.4 Orgnization

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. OFDMA-based random access employs binary exponential backoff and MU PHY under Trigger-based MU UL. It is absolutely different from [13], since [13] is a CSMA-like random access while OFDMA-based random access is an Aloha-like random access. We know that [4] proposes an accurate Markov chain model for DCF, which is CSMA-like. In this thesis, we show that how to extend the 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 their queues are never empty. The saturated analysis is based on the key assumption of constant and 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 have system parameters setting dynamically by AP, we evaluate effect of a variety of parameter sets and at last propose rules for AP to configure the parameter set.

The thesis is organized as follows. More explanations of 802.11ax features are given in section 2.1. In section 2.2, a detailed illustration of OFDMA-based random access procedure is presented. Chapter 3 contains the system model and derivation of two metrics, including system efficiency and access delay. Simulation which helps validate the system model is presented in this chapter. Then chapter 4 is the performance evaluation of optimal performance and checks the impact of system parameters on performance. At last rules of configuring system parameters are listed. Chapter 5 is the conclusion remark.

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 MAC, 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, multi-user (MU) PHY is issued in IEEE 802.11ax to improve the system performance[8]. In this chapter, we first introduce 802.11ax feature, MU PHY, then illustrate the OFDMA-based random access mechanism.

2.1 Multi-User PHY

2.1.1 PHY

While legacy 802.11 specifies 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 MU PHY with OFDMA, allowing multiple STAs to access channel simultaneously. It should help mitigate contention and collision.

The channel in 802.11ax is more fine-grained, defined as resource unit (RU) in figure 2.1. The smallest RU is 26-tone, with which a legacy 20 MHz channel 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

RU type	CBW20	CBW40	CBW80	CBW80+80 and CBW160
26-tone RU	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	N/A	N/A	N/A	1-SU/MU-MIMO

Figure 2.1: Maximum number of RUs for each channel width

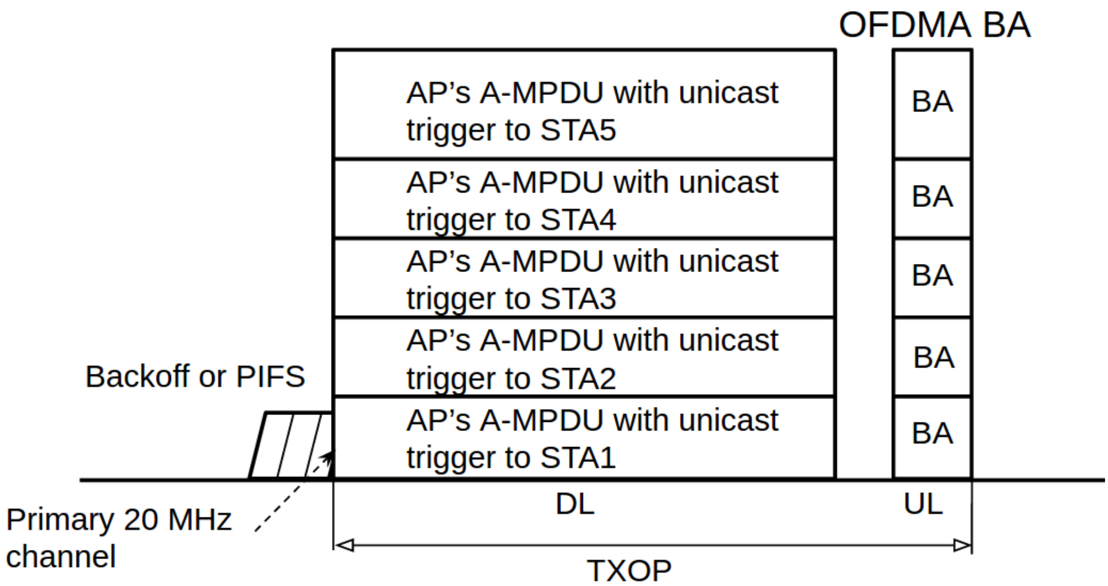


Figure 2.2: MU DL of 802.11ax

figure 2.1, multiple 20 MHz channels can be aggregated to be utilized by a BSS, which is called Channel Bonding. 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, DL 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.

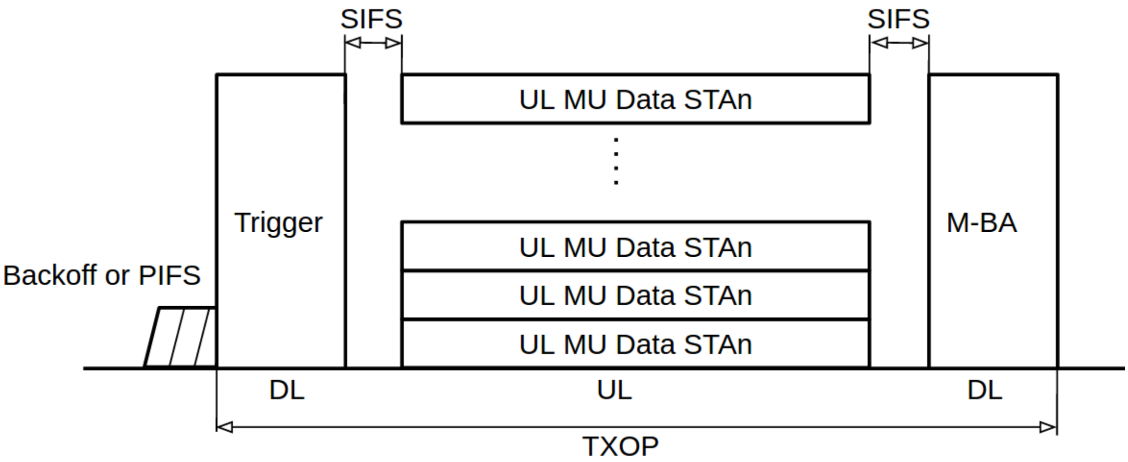


Figure 2.3: Trigger-based MU UL of 802.11ax

2.1.2 MAC

802.11ax MAC is still based on DCF. However, only AP follows DCF. HE-STAs are scheduled by AP. 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 UL packet. In this way, stations are able to access channel with RU scheduled by trigger frame transmitted by AP. The trigger frame format is as figure 2.4. Since the standard is in progress, many fields remain to be determined (TBD).

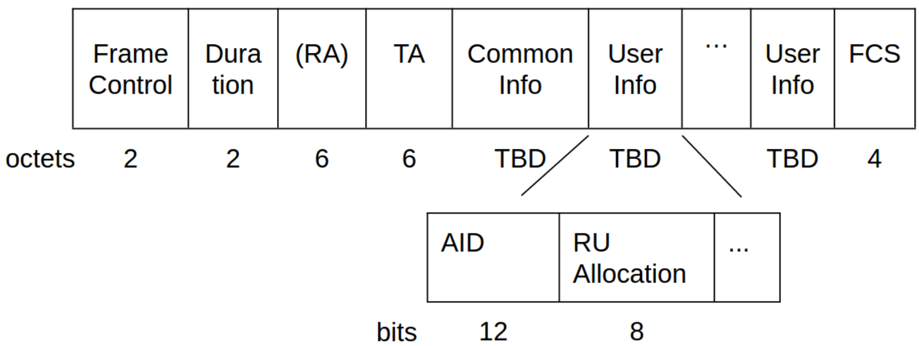


Figure 2.4: Trigger Frame format

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

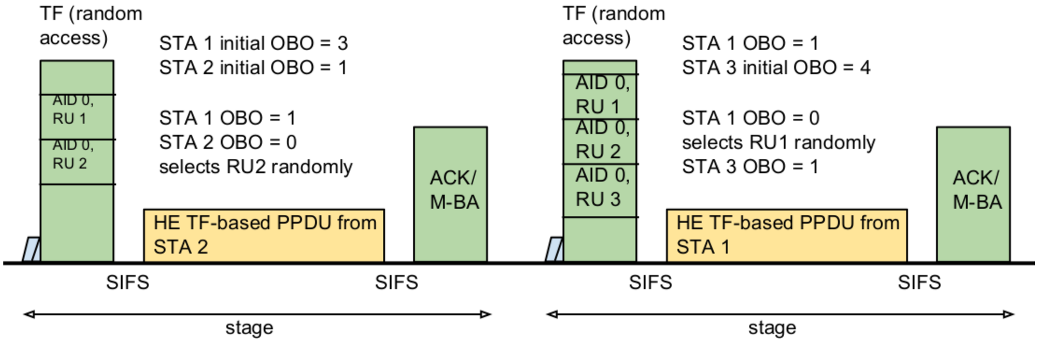


Figure 2.5: Illustration of OFDMA-based random access

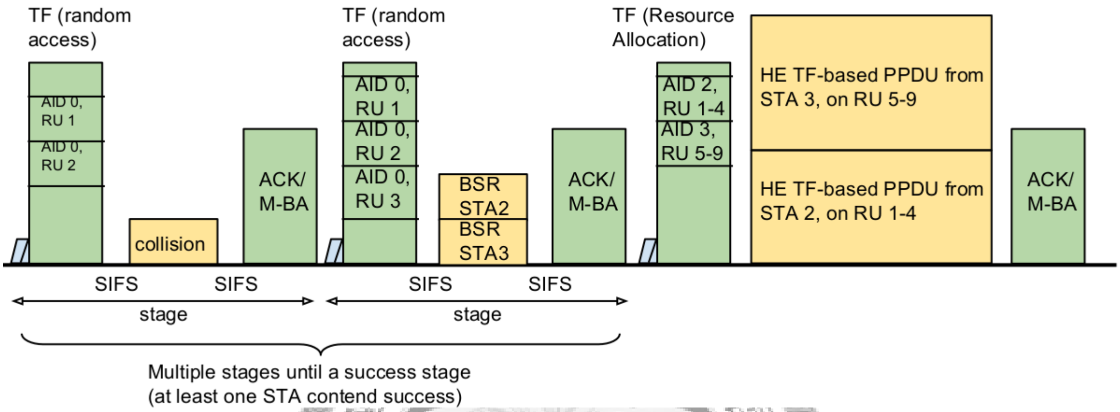


Figure 2.6: An example of OFDMA-based random access for UL in 802.11ax

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[10]. It is also out of scope of this thesis.

2.2 802.11ax Random Access Illustration

As stated above, legacy IEEE 802.11 MAC is a 20 MHz 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 system parameters are set by AP dynamically. The procedure is of course more complicated and flexible. We first illustrate the OFDMA-based random access procedure then give one use case of the random access.

Different from legacy 802.11 where parameters like contention window are pre-set at hardware of station, all the parameters are configured by AP in 802.11ax. 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-STAs need to 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 and OCW is retrieved from RAPS sent by AP. Then the OBO subtracts M, 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 RUs 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 contending. The OFDMA-based random access is a three-way handshake, which is totally called a stage. It is worth reminding that the stage in this thesis is a concept of interval[1], not the backoff stage in papers[4]. 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 so that 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 simplifies analysis.

Following is a use case of OFDMA-based random access as figure 2.6. When HE-STAs want 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. Then stations transmit UL data packets with the allocated RUs.

Other use cases could borrow the same random access procedure. 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.

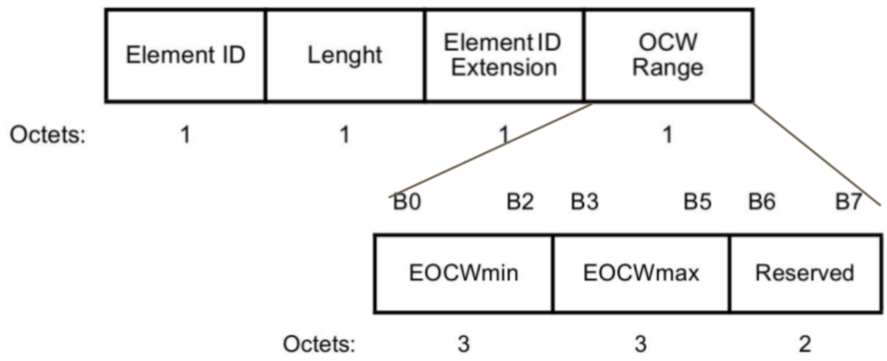


Figure 2.7: Random Access Parameter Set (RAPS) Element

Chapter 3

System Model

One of main contribution of this thesis 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[4]. However, DCF is CSMA-like random access while OFDMA-based random access is an Aloha-like random access. Fortunately, the Markov chain model mainly model the back-off mechanism, so it could be modified not much to model the Aloha-like OFDMA-based random access. Here, for the brand new OFDMA-based random access, we generate a new Markov chain model. In this analysis, we 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.

Before generating Markov Chain model, we need to clarify concept of time in this mechanism. The OFDMA-based random access is a three-way handshake procedure, AP initiating a TF, followed with STAs' sending request, then AP responding the request with ACK. The whole procedure is so-called ”stage”. Actually, we have known that in legacy 802.11 DCF, time is measured in slot, which is a unit of time. Here, time is measured in

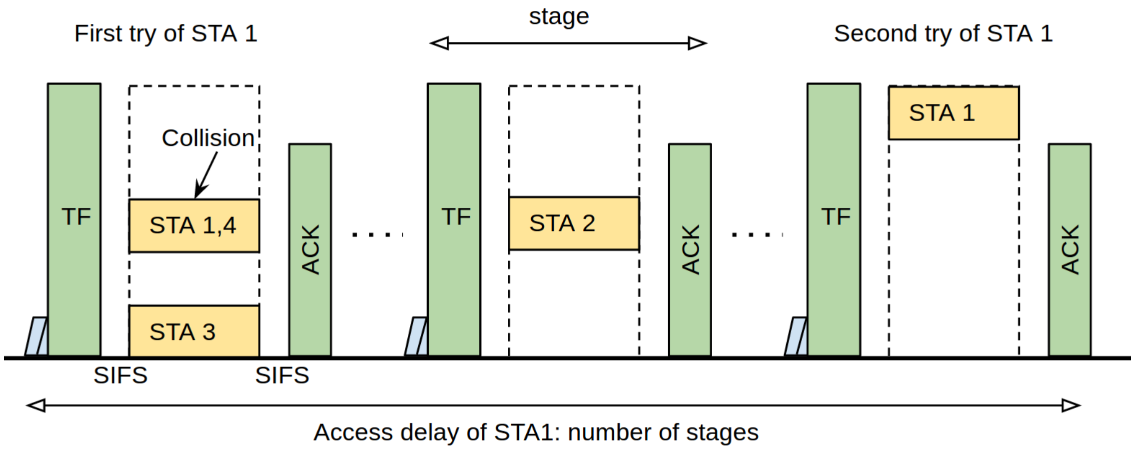


Figure 3.1: Concept of time in OFDMA-based random access

stage, which is a discrete time and is not synchronized with physical time. Stages should be mapped with ”slot” in legacy random access mechanism. Thus, access delay in this mechanism will be number of stages for station to access channel.

3.1 Packet Transmission Probability

Since 802.11ax implements OFDMA and trigger-based UL, 802.11ax stations won't contend with AP under this situation. To estimate the performance of the OFDMA-based random access mechanism, we assume a saturated condition that each station always has requests to transmit. In the above 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. Consider a fixed number n of contending stations.

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
D	access delay, # of stages for a station to succeed in contending
D_s	# of stages until a successful stage

M represents the number of RU for random access in a stage.

Let $b(t)$ be the stochastic process representing the backoff time counter for a given station. A discrete and integer time scale is adopted: t and $t+1$ correspond to the beginning of two consecutive stage times, and the backoff time counter of each station decrements at the beginning of each stage. Note that this discrete time scale does not directly relates to the physical time. In fact, as illustrated in figure 3.1, time interval between two consecutive stages is variable. And since the OFDMA-based random access in MU PHY is kind of Aloha random access, the backoff counter will only be frozen outside the stage period. The request packet is contained in a stage, thus the time interval between two stages is just a stage, which is absolutely different with Bianchi's model. In Bianchi's model of DCF, the time interval between two slot time beginnings may be much longer than the slot time size, as it may include a packet transmission. That's why in section 3.2, we could generate easy system efficiency rather than a complicate throughput as in [4].

Since the value of the backoff counter of each station depends also on its transmission history (e.g., how many retransmission the head-of-line packet has suffered), the stochastic process $b(t)$ is non-Markovian. However, define convenience $W_0 = OCW_{min}$. Let m, "maximum backoff level", be the value such that $OCW_{max} = 2^m W_0$, and let's adopt the notation W_i, the OFDMA contention window (OCW) at i^{th} backoff level, with relationship $W_i = 2W_{i-1} + 1$, where $i \in (0, m)$ is called "backoff level". Let $s(t)$ be the stochastic process representing the backoff level $(0, ..., m)$ of the station at time t.

The key approximation in our model is that, at each transmission attempt, and regardless of the number of retransmissions suffered, each packet collides with constant and independent probability p. It is intuitive that this assumption results more accurate as long as W_0 and n get larger. p will be referred to as "conditional collision probability", meaning that this is the probability of a collision seen by a packet being transmitted on the channel.

Once independence is assumed, and p is supposed to be a constant value, the bi-dimensional process $\{s(t), b(t)\}$ could be modeled with Markov chain as in figure3.2. There mainly two differences compared with Bianchi's Markov chain. Firstly, since states $(i, 0 \sim M)$ all means station could access RU, we could merge these states into one state,

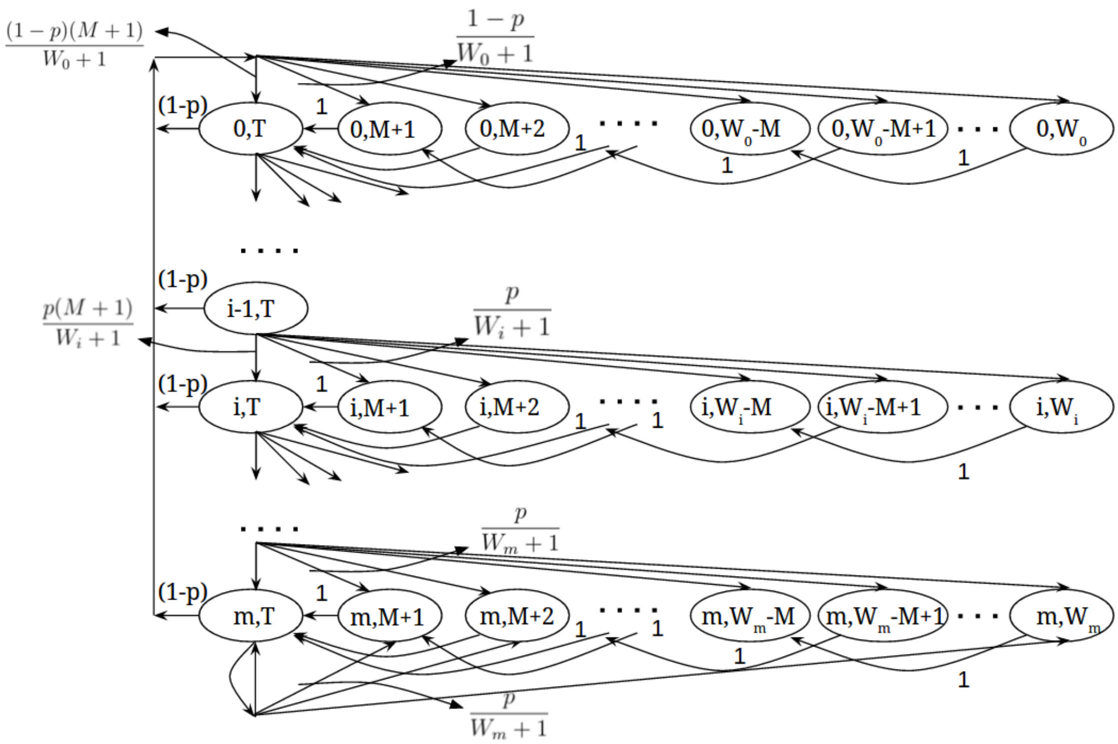


Figure 3.2: Markov Chain model for the backoff window size

denoted by (i, T). Secondly, at beginning of each stage, the backoff counter will decrease the value of M, instead of 1, which is depicted in chapter 2.

Let's assume $P\{i_1, k_1|i_0, k_0\} = P\{s(t+1) = i_1, b(t+1) = k_1|s(t) = i_0, b(t) = k_0\}$. In this Markov Chain, the only non null one-step transition probabilities are

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

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 $k = T$

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

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

Then, owing to the chain regularities, for each $k \in [T, W_i]$, it is

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

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 which means the sum of each row of states in figure 3.2, we obtain equation 3.5.

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

For convenience, 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 are capable of summing all the states to have equation 3.7.

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

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

We can now express τ, the probability of a station transmit a request at a randomly selected stage. As any transmission occurs when the backoff time counter is equal to zero, regardless of the backoff level, it is

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

As a side note, it is interesting to highlight that, when $m = 0$ (i.e., no exponential backoff is considered), 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 degraded to

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

further simplified that $M = 1$ and $X_0 = \frac{W_0^2 - W_0}{2}$, then

$$\begin{aligned}\tau = b_{0,T} &= \frac{W_0+1}{W_0+1+X_0} \\ &= \frac{2(W_0+1)}{W_0^2+W_0+2},\end{aligned} \tag{3.10}$$

which is different from [9] since the OFDMA-based random access is Aloha-like not CSMA-like random access. Whatever, the probability τ results to be independent of p.

On the other hand, in general, τ depends on the conditional collision probability p, which is still unknown. To find the value of p it is sufficient to note that the probability p that a transmitted packet encounters a collisions, is the probability that, in a stage, at least one of the $n-1$ remaining stations transmit on the selected RU. The fundamental independence assumption given above implies that each transmission "sees" the system in the same state, i.e., the steady state. At steady state, each remaining station transmits a packet with probability τ. This yields

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

Rewrite the equation 3.11, $\tau^\star = \left(1 - (1-p)^{\frac{1}{n-1}}\right) M$. To obtain transmission probability 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 D. 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 D_s. It helps design whole MU UL transmission procedure. Here, our concern is mainly on n_s, system efficiency and access delay all of which are purely related to random access procedure. The other metric D_s 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 so that we could compare among different M, thus system efficiency 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

Access delay D is defined as number of stages needed for a station to succeed in contending. This access delay is different from legacy access delay since the concept of time here is not corresponding with physical time. We measure the time as number of stages. Access delay D follows geometric distribution with parameter $P_{s\_station}$, which is obtained just now. Thus the expected value of access delay of request frame, $E[D]$, is

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

Then another interesting metric which is not our focus, denoted by D_s, 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 D_s follows geometric distribution with parameter P_{s_stage},

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

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 D. Actually, only two variables are concerned, n_s and D. 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 as in section 2.2. We run the simulation with variety of parameter sets $\{M, OCW_{min}, OCW_{max}\}$ and collects the information of the two variables, n_s and D. The values of results from both analysis and simulation are given in figure 3.3 and table 3.2. All simulation results are obtained from a long-run simulation. The results show that the Markov model precisely predict the steady state 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

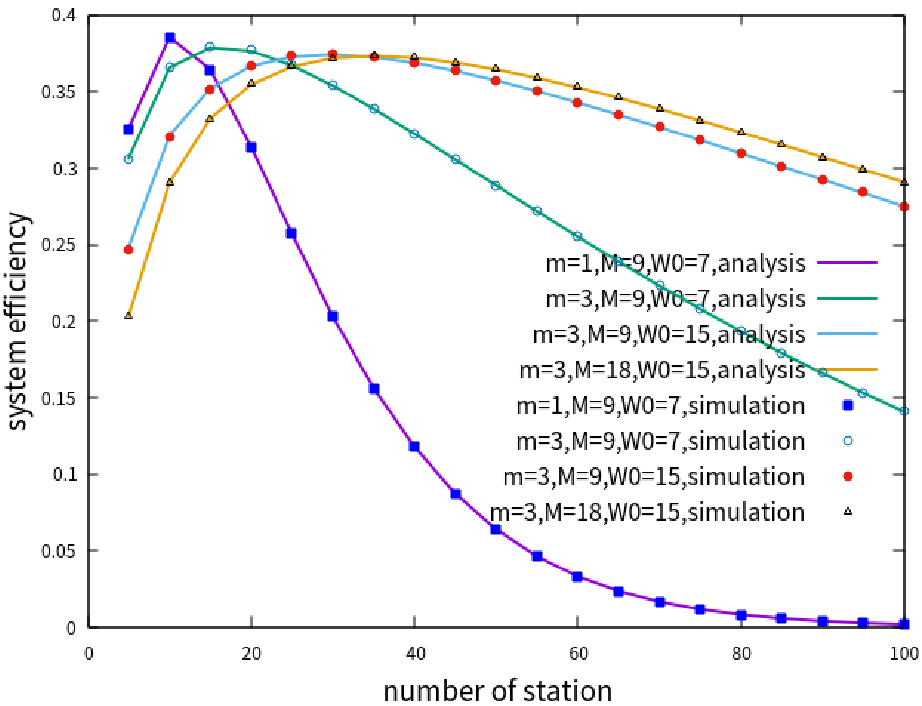


Figure 3.3: System efficiency: Analysis versus Simulation

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.

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

Thus the limit of system efficiency, based on infinite 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

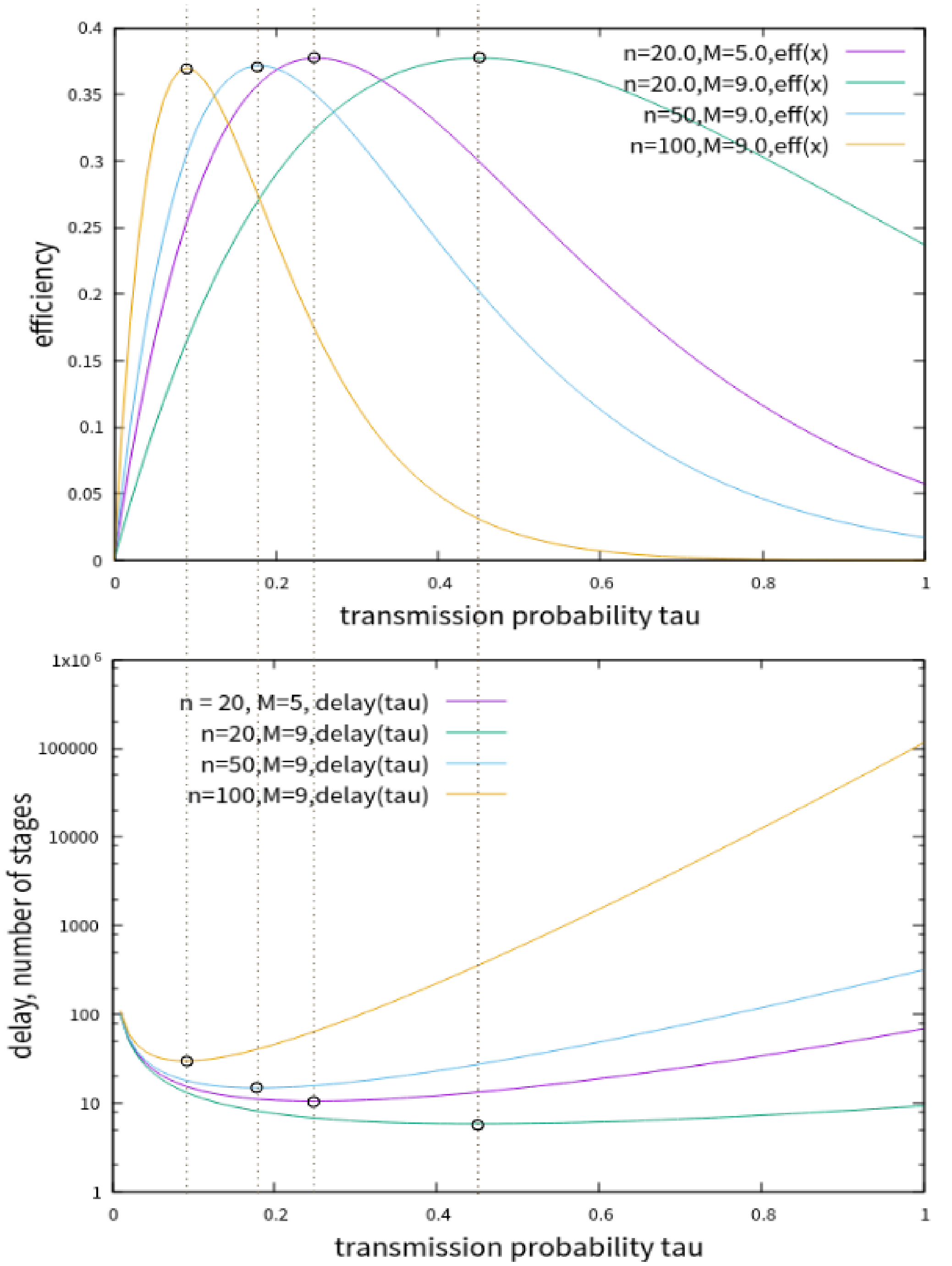


Figure 4.1: Efficiency and access delay versus transmission probability τ

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 $\tau^{\star} = min\{1, M/n\}$.

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 is plotted corresponding to equation 3.13 and 3.14. 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 (RUs for random access in a stage), W_0 (initial contention window) m (backoff levels) or W_m (the maximum 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 system parameter set $\{M, W_0, W_m\}$ 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, n_s (number of stations who succeed in contending in a stage), system efficiency and D (access delay), under various parameter sets. With above analysis, 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 $\{M, OCW_{min}, OCW_{max}\}$.

4.2.1 RUs for Random Access M

Equation 4.1 indicates that M, the number of RUs for random access, has nothing to do with maximum system efficiency. However, larger M is better for n_s and D according to equation 4.2 and 4.4. More explaination are given later to validate the statement.

In figure 4.2, the maximum system efficiency is the same. The difference is ”when” the optimal point will be. For larger M, the optimal number of stations is larger, given by M/n. It is also intuitive.

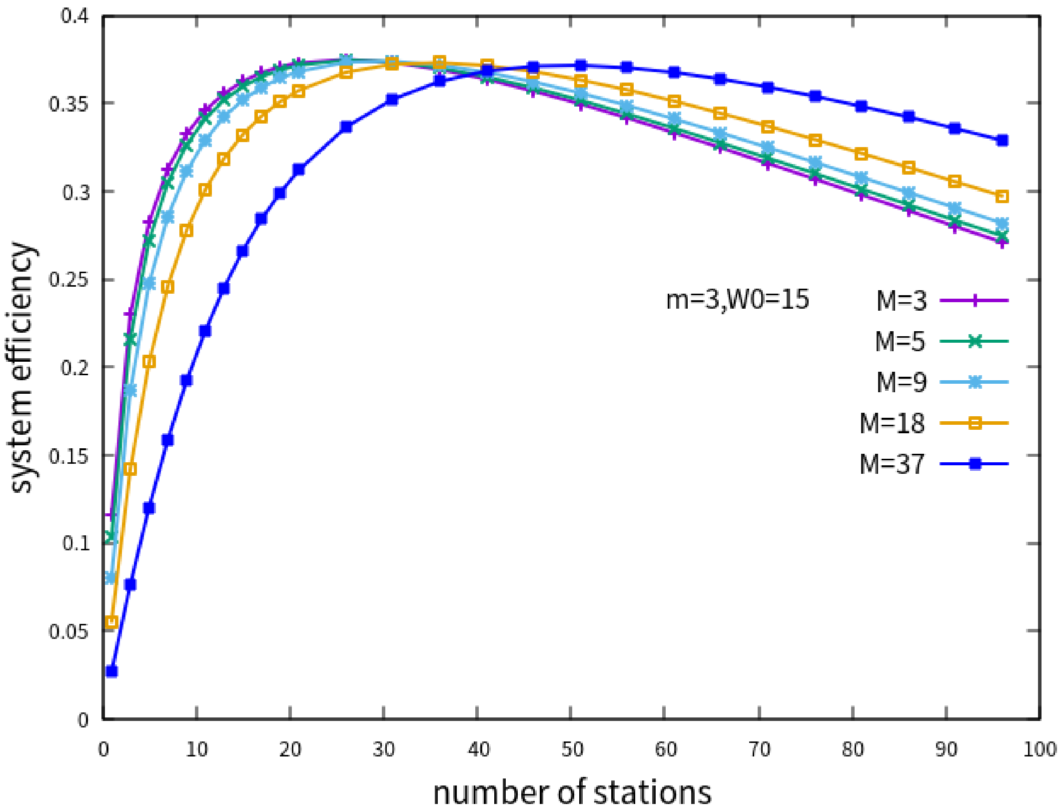
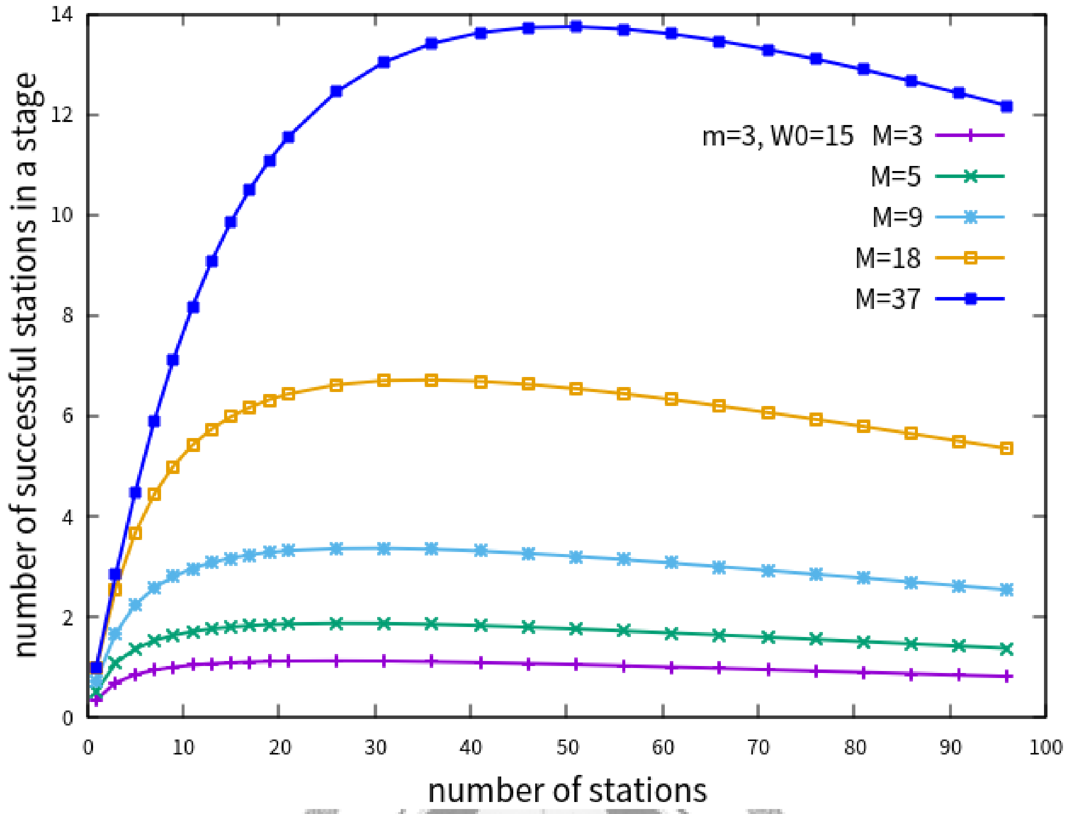


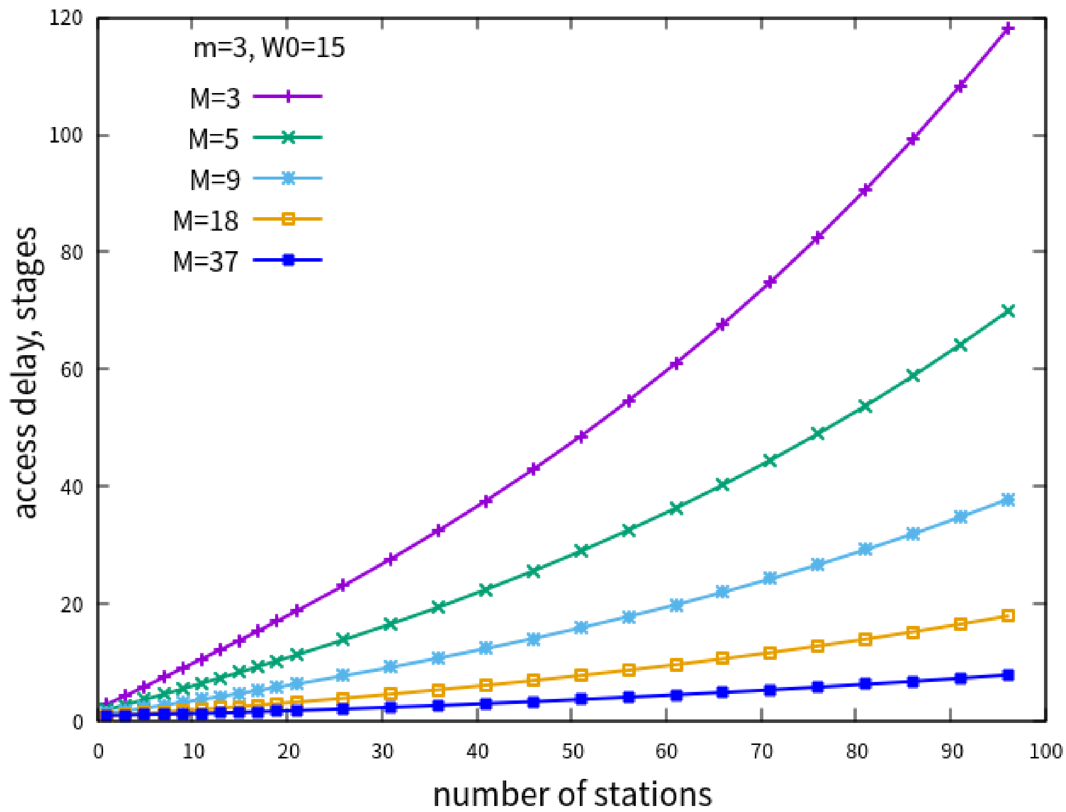
Figure 4.2: System efficiency versus number of stations

In figure 4.3b, the larger M will linearly decrease the access delay of station. The figure is consistent with the equation 4.4.

More practically, we present the number of successful stations in a single stage versus number of stations in figure 4.3a. 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 proportional to M. Above all, when AP allocates



(a) Number of successful stations in a single stage versus number of stations



(b) Access delay versus number of stations

Figure 4.3: Configure M

RUs for random access, the AP will sense channels first then allocates as many RUs, which are sensed idle, for random access as possible.

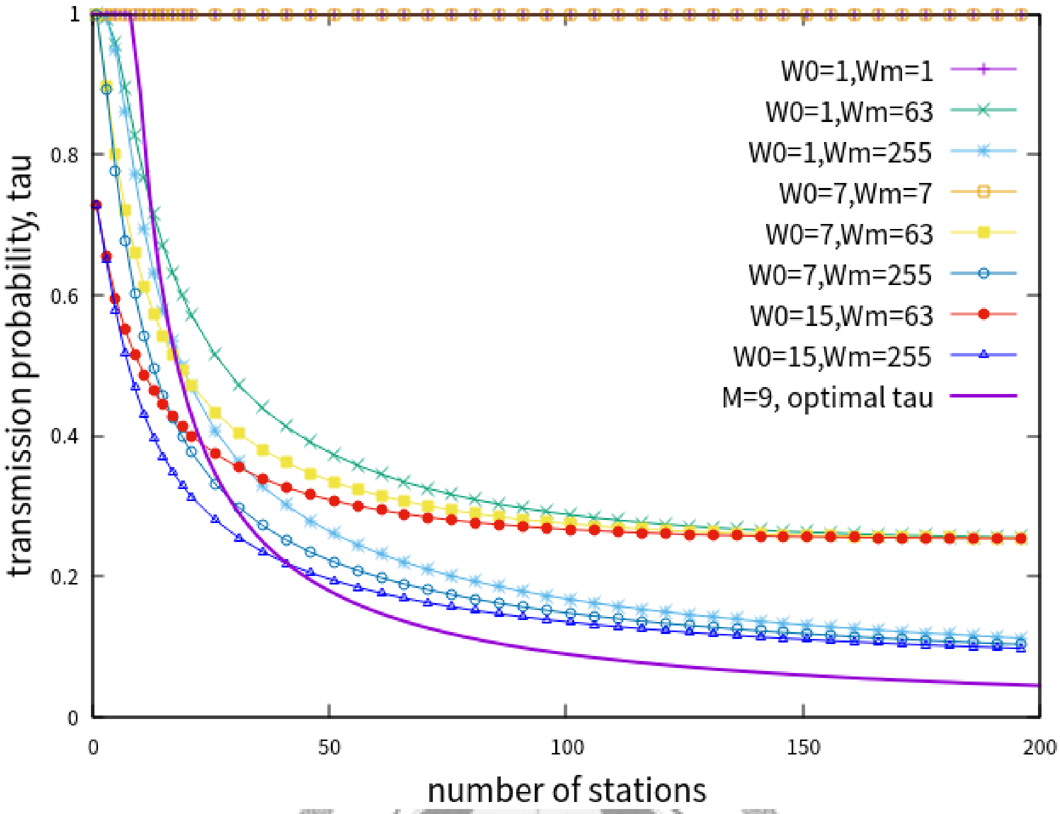
4.2.2 Initial and max Contention Window (OCW_{min}, OCW_{max})

Different from legacy 802.11 where backoff mechanism is pre-set in hardware of stations, the initial and maximum contention window (OCW_{min}, OCW_{max}) are allocated in beacon frame sent by AP. Thus, the configuration of backoff mechanism becomes dynamic, which means that it could be configured according to the scenario, especially the number of stations. With the M being determined as large as possible, it is more complicated algorithm to adaptive tune OCW_{min}, OCW_{max} 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 expression of τ determined by system parameters W_0 and W_m. However, we could find the rules by checking a variety of parameter sets.

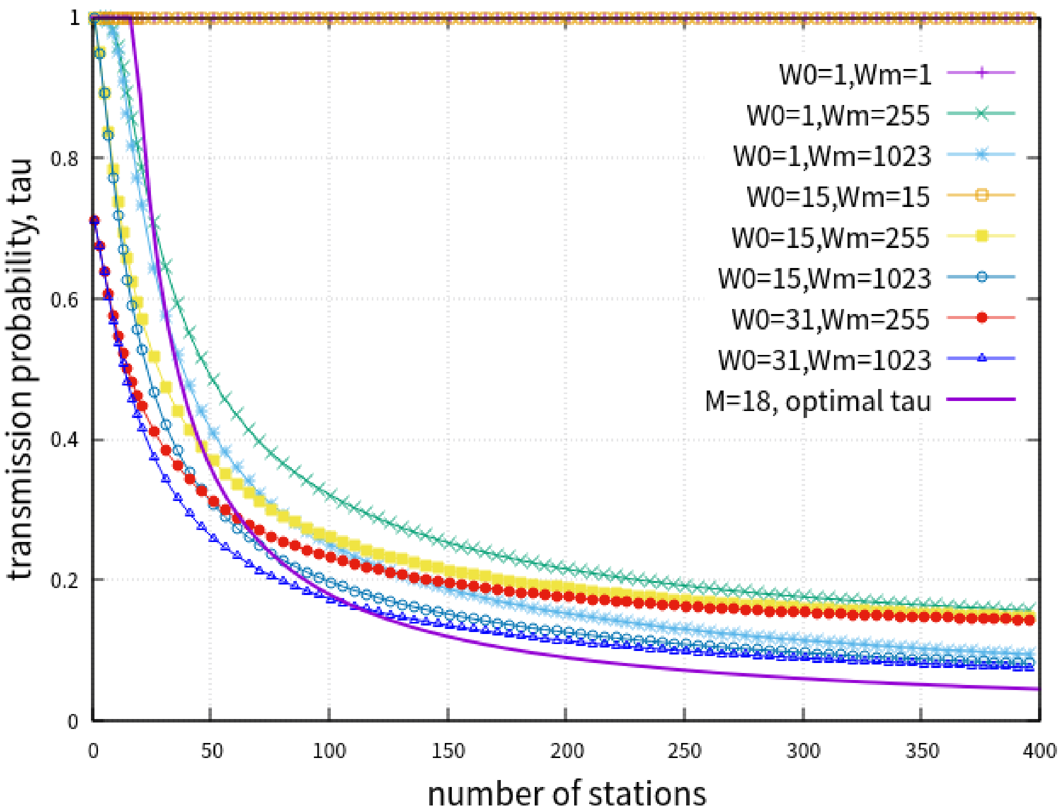
Figure 4.4 shows case 1 ($M = 9$) and case 2 ($M = 18$), from both of which we could generalize some rules between τ and parameters OCW_{min}, OCW_{max}. In the figure, the purple line without point is the optimal τ, which is given according to $\tau^\star = min\{1, M/n\}$. As stated above, we need to find a tuning of OCW_{min}, OCW_{max} so that τ approaches the optimal line. The rules are listed following.

Firstly, 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 $n = 1$. A special situation is when $W_0 < M$, $\tau = 1$ at $n = 1$. That's why cases in figure 4.4 have two different start points. For optimal transmission probability $\tau^\star$, when $n \leq M$, $\tau^\star = 1$. A special case of $m = 0$, which means $W_m = W_0$, results in constant transmission probability equal to 1, which is perfect match with $\tau^\star$ at $n \leq M$. Thus, if given $n \leq M$, the optimal configuration will be $OCW_{max} = OCW_{min} < M$.

Secondly, W_m determines limit of the τ, i.e., where the line will converge. Lines with the same W_m will converge to a same value. To see the tendency of lines, I draw the two figures 4.4a and 4.4b with n in range $[0, 200]$ and $[0, 400]$ respectively. And both the two figures validate the above statement. And larger W_m is closer to optimal transmission



(a) Case 1, given $M = 9$



(b) Case 1, given $M = 18$

Figure 4.4: Transmission probability versus number of stations

probability when n is large. 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.

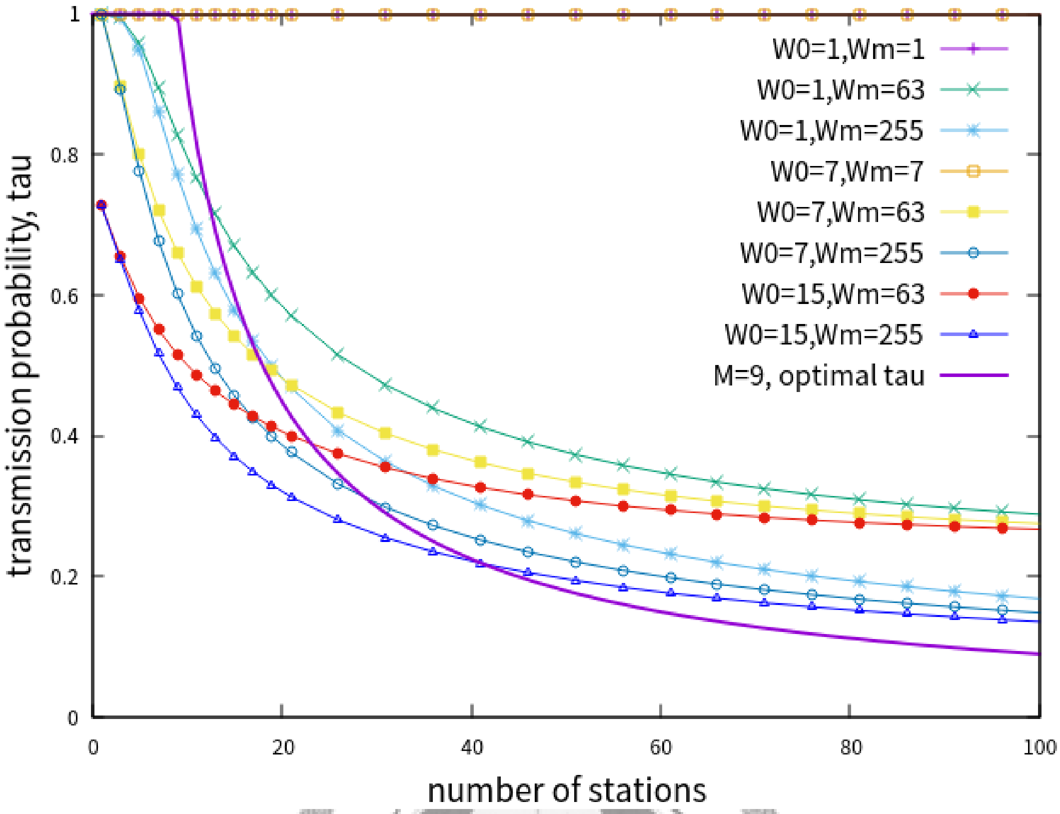
Then, we draw two figures with x axis range $[0, 100]$ to find more rules as in figure 4.5. From the two figures 4.5a and 4.5b we find another rule that if $W_0 = 1$ which is the minimum value, there will be a flat start of τ. What's good is that the flat start is closer to $\tau^\star$ when $n \leq M$.

Based on above observation, we find conclude that W_0 has significant influence on small $n \leq M$, while W_m affects n is large or $n > M$. Afterwards, in the next two subsections, we check the system efficiency and access delay under different parameter sets of $\{W_0, W_m\}$, with which we could find explicit relationship between the parameter and performance.

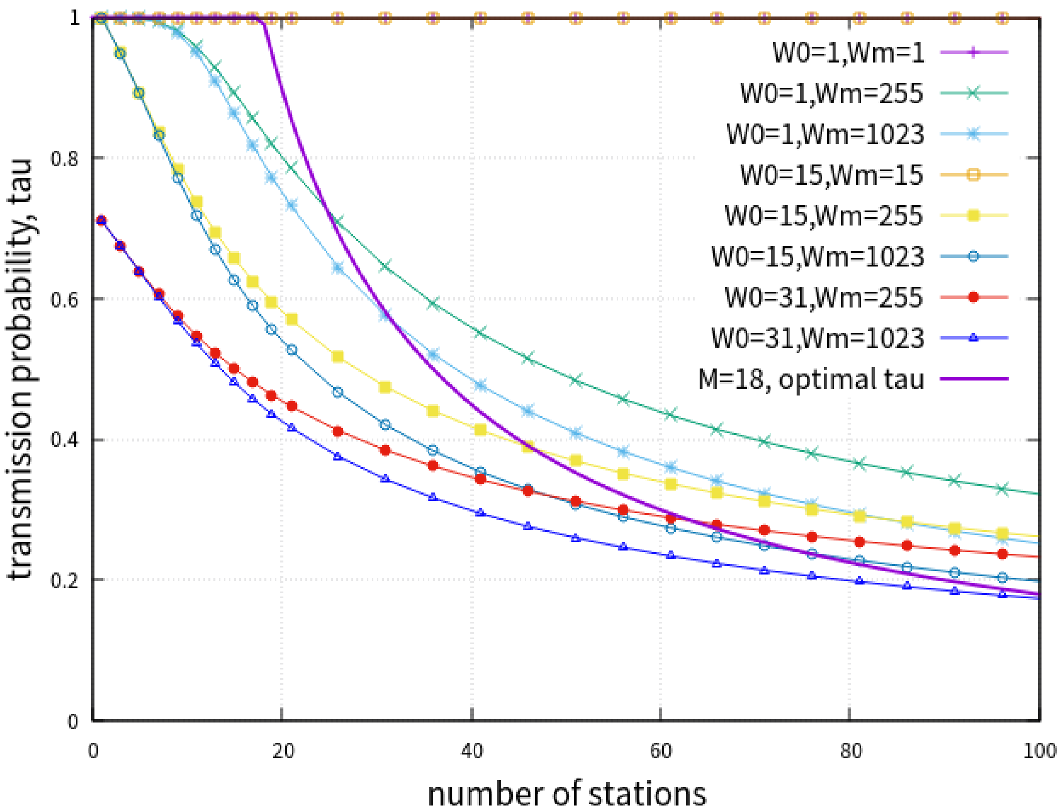
Configure OCW_{max}

With above rough rules, we estimate the effects of OCW_{max} first by setting different OCW_{max} while given $OCW_{min} = 1$ and $M = 9$. It is because small OCW_{min} is good for situation of small n. Actually the data we use to generate the figures are the same as that for figure 4.4a. For figure 4.6a, we display three of them to clearly show relationship between system efficiency and OCW_{max}. And from the figure, it is apparent that larger OCW_{max} is better for system efficiency. The result corresponds to the second rule we obtain when estimating the transmission probability τ. What's more, the access delay also validates the same result. And since we use the same data with that in figure 4.4a, we find that the lines which converge in figure 4.4a also have the same tendency in figure 4.6b.

As stated in last section that OCW_{max} has significant influence on situation of large n, n is number of contending stations. With increasing n, larger OCW_{max} will obtain larger gain. Therefore, we have a rule that the larger OCW_{max}, the better.

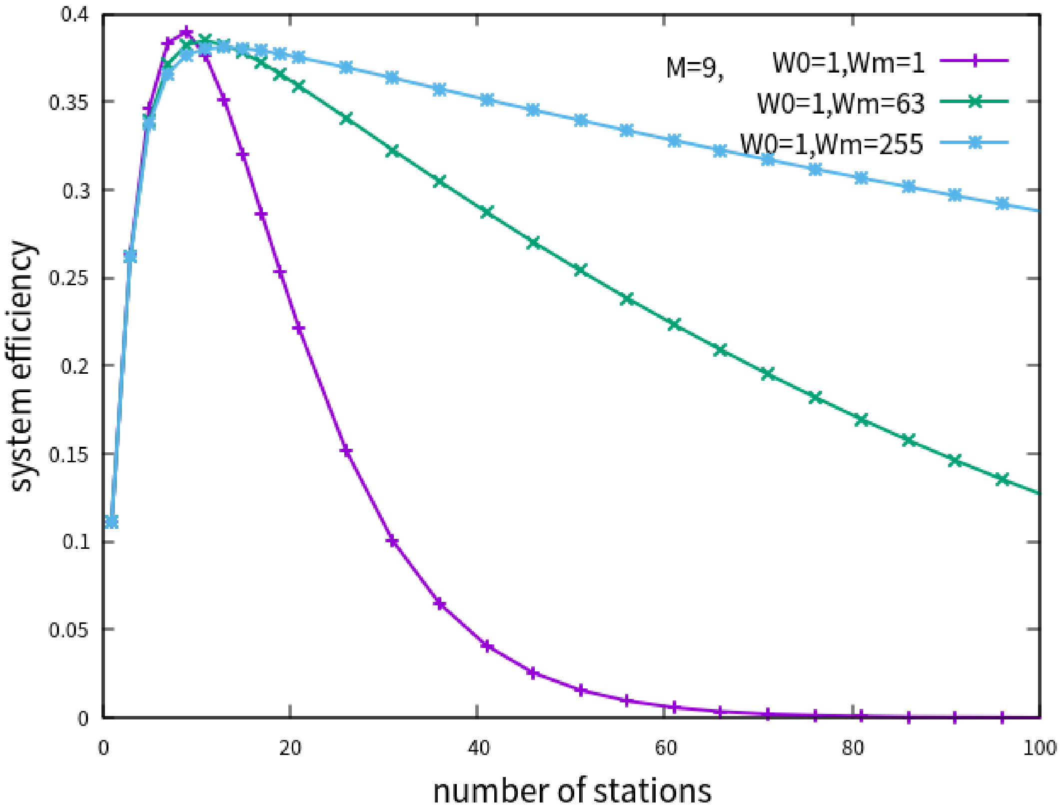


(a) Case 1, given $M = 9$

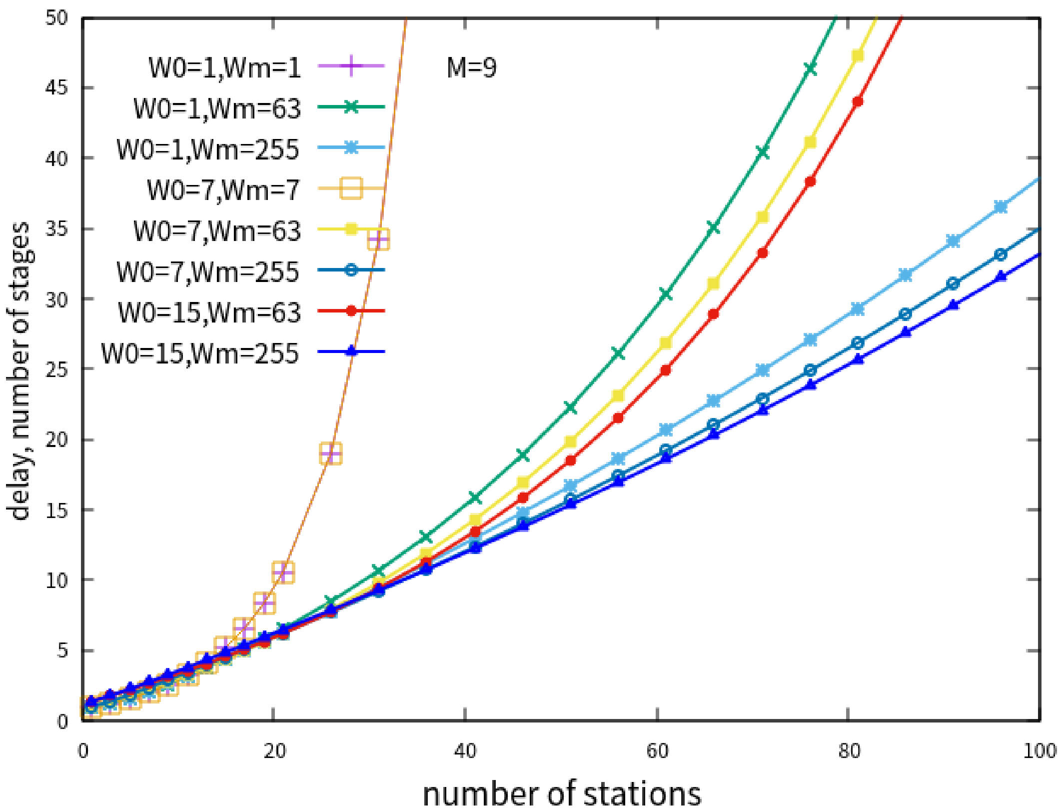


(b) Case 1, given $M = 18$

Figure 4.5: Details of transmission probability versus number of stations when $n \leq 100$



(a) System efficiency versus number of stations



(b) Access delay versus number of stations

Figure 4.6: Example of Configuring OCW_{max}, given $M = 9$

Configure OCW_{min}

Similarly, to estimate the relationship between performance and OCW_{min}, we compare the performance between different OCW_{min} while given fixed $OCW_{max} = 1023$, which has been validated that large OCW_{max} is better, and $M = 18$. Firstly, we claimed in section 4.2.2 that $W_0 = W_m \leq M$ is the perfect configuration in situation of $n \leq M$. It is again validated here that it has the maximum system efficiency and minimum access delay in situation of $n \leq M$. Secondly, since OCW_{min} determines the start of line, i.e., $n = 1$, it has significant influence on small n. From figure 4.7a and 4.7b, we find larger $OCW_{min} = 127$ has lower system efficiency and longer access delay. And as stated before, $W_0 = 15$ has close performance with $W_0 = 1$ since $W_0 < M$ will be similar for situation of small n.

Therefore, we generate a rule that the smaller OCW_{min}, the better. For a special situation that $n \leq M$, we could configure $OCW_{min} = OCW_{max} < M$, which will result in perfect performance. However, larger OCW_{max} smaller OCW_{min} is closely approach to optimal performance.

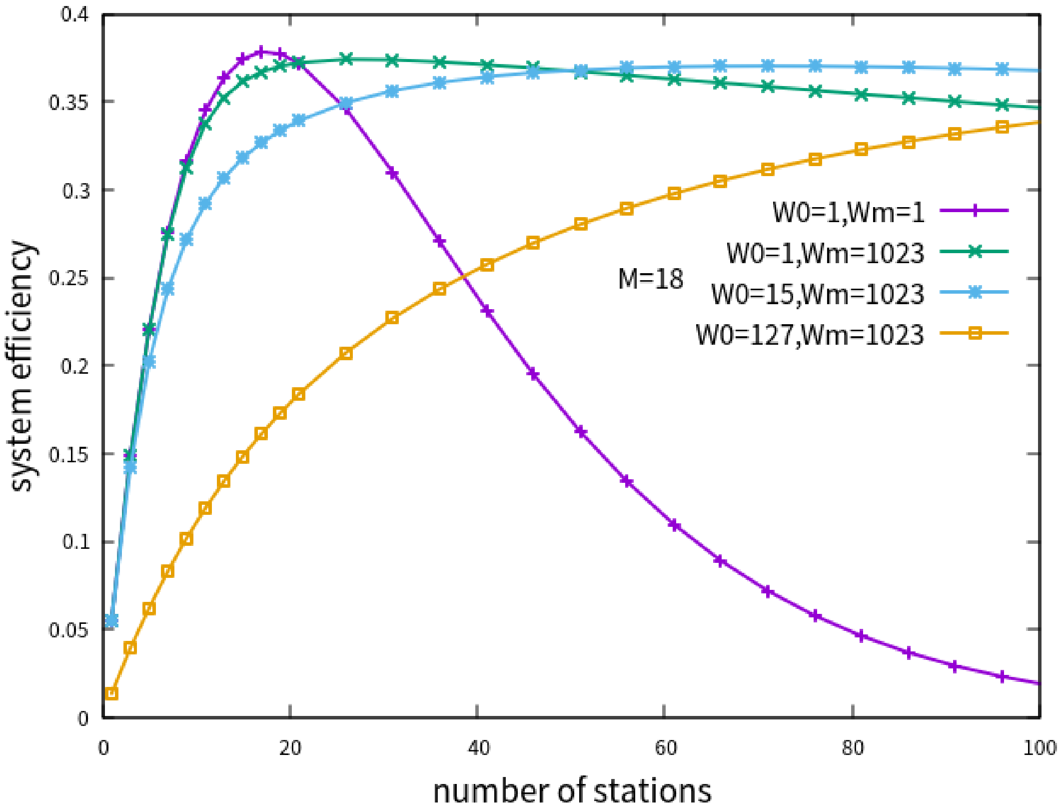
4.2.3 Rules for configuring $\{M, OCW_{min}, OCW_{max}\}$

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

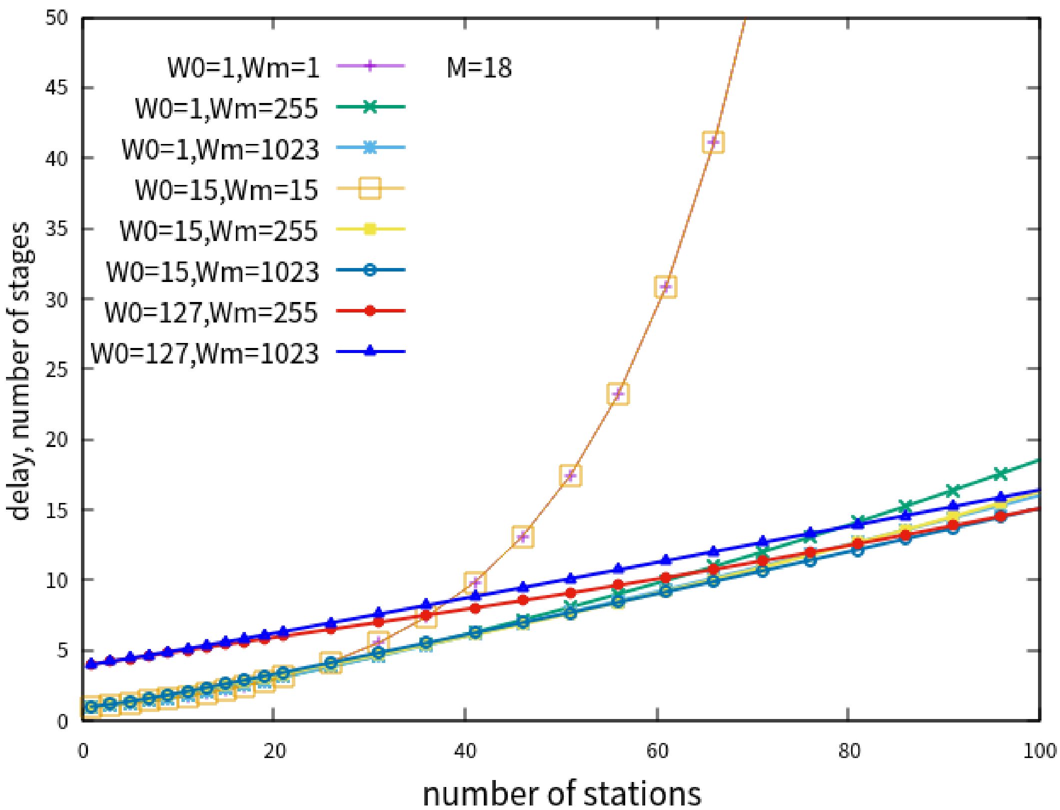
Rule 1 Large M

Rule 2 OCW_{min}, OCW_{max}

- small OCW_{min} and large OCW_{max}
- If given $n \leq M$
  - $OCW_{max} = OCW_{min} < M$



(a) System efficiency versus number of stations



(b) Access delay versus number of stations

Figure 4.7: Example of Configuring OCW_{min}, given $M = 18$

Chapter 5

Conclusion

In this thesis, we first expose that the bottleneck of legacy 802.11 is located at its MAC, instability of DCF and unfair queueing problem. Then we introduce 802.11ax as a solution which aimed at high efficient WLAN (HEW). One of the important features of 802.11ax is OFDMA-based random access, which is MU random access in IEEE 802.11ax MAC. The system parameters are configured by AP dynamically, so it is more flexible and more complicated.

Afterwards, we extend Bianchi's Markov chain model of DCF to model the OFDMA-based random access for its simplicity and accuracy. With the model we do saturation analysis to depict the steady state behavior of the mechanism. Simulation validates the model. Then we could estimate the impact of a parameter set $\{M, OCW_{min}, OCW_{max}\}$ on system efficiency and access delay, where M is the number of RUs for random access, and OCW_{min}, OCW_{max} is the initial and maximum OFDMA contention window. At last, rules of configuration of the parameter set aimed at approaching the optimal transmission probability $\tau^{\star}$ is proposed for AP with or without given number of contending stations.

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