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Performance Enhancement of IEEE 802.11AX in Ultra-Dense Wireless Networks

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Abstract

IEEE 802.11ax, which is one emerging WLAN standard, aims at providing highly efficient communication in ultra-dense wireless networks. However, due to a large number of stations (STAs) in dense deployment scenarios and diverse services to be supported, there are many technical challenges to be overcome. Firstly, the potential high packet collision rate significantly degrades the network efficiency of WLAN. In this thesis, we propose an adaptive station (STA) grouping scheme to overcome this challenge in IEEE 802.11ax using Uplink OFDMA Random Access (UORA). In order to achieve optimal utilization efficiency of resource units (RUs), we first analyze the relationship between group size and RU efficiency. Based on this result, an adaptive STA grouping algorithm is proposed to cope with the performance fluctuation of 802.11ax due to remainder stations after grouping. The analysis and simulation results demonstrate that our adaptive grouping algorithm dramatically improves the performance of both the overall system and each STA in the ultra-dense wireless network.

Meanwhile, due to the limited RU efficiency of UORA, we adopt the proposed grouping scheme in the Buffer State Report (BSR) based two-stage mechanism (BTM) to enhance the Uplink (UL) Multi-user (MU) access in 802.11ax. Then we propose an adaptive BTM grouping scheme. The analysis results of average RU for each STA, average throughput of the whole system and each STA are derived. The numerical results show that the proposed adaptive grouping scheme provides 2.55, 413.02 and 3712.04 times gains in throughput compared with the UORA grouping, conventional BTM and conventional UORA, respectively.

Furthermore, in order to provide better QoS experience in the ultra-dense network with diverse IoT services, we propose a Hybrid BTM Grouping algorithm to guarantee the QoS requirement from high priority STAs. The concept of "QoS Utility" is introduced to evaluate the satisfaction of transmission. The numerical results demonstrate that the proposed Hybrid BTM grouping scheme has better performance in BSR delivery rate as well as QoS utility than the conventional BTM grouping.

Keywords: IEEE 802.11ax, Uplink OFDMA Random Access (UORA), Buffer Status Report (BSR), Target Wake Time (TWT), Adaptive Grouping, QoS, Utility function, Latency.

He who stands on his tiptoes
can not stand firm;
He who walks with great strides
can not go far.

–*Laozi*

企者不立，跨者不行，自見者不明，自是者不彰，自伐者無功，自矜者不長.

– 老子

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List of Abbreviations

AI	Artificial Intelligence
AP	Access Point
BSR	Buffer Status Report
BSRP-TF	Buffer Status Report Poll Trigger Frame
BTM	BSR-based two-stage mechanism
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
DIFS	Distributed coordination function Interframe Space
HE TB PPDU	High Efficiency Trigger-based Presentation Protocol Data Unit
HEW	High Efficiency Wireless Local Area Network
IoT	Internet-of-Thing
MAC	Media Access Control
M-BA	Multi-STA BlockAck
MCS	Modulation and Coding Scheme
MIMO	Multiple-Input Multiple-Output
MU	Multi-user
OBO	OFDMA Backoff
OCW	OFDMA Contention Window
OFDM	Orthogonal frequency-division multiplexing
OFDMA	Orthogonal Frequency-Division Multiple Access
PHY	Physical

PPDU	Presentation Protocol Data Unit
QoS	Quality of Service
RA-RU	Resource Unit for Random Access
RU	Resource Unit
SIFS	Short Inter-Frame Space
STA	Stations
SP	Service Periods
TWT	Target Wake Time
UORA	Uplink OFDMA-based Random Access
Wi-Fi	Wireless Fidelity
WLAN	Wireless Local Area Network

Chapter 1

Introduction

1.1 Overview

The ever-evolving wireless technologies and their ongoing convergence with vertical industries are fundamentally transforming our society through diverse applications and services enabled by Internet-of-Things (IoT). The fast transformation of our industry and society also raise many new challenges to current wireless communication techniques. According to the industrial report from Huawei, due to the falling cost of IoT devices, there will be 40 billion smart devices expected to be deployed worldwide by 2025 [1]. Meanwhile, most of the wireless devices are deployed in the urban area, according to [2]. With a rising number of IoT devices deployed in the limited urban area, the future IoT network is expected as the "ultra-dense" deployed network, which becomes a critical challenge to current wireless communication techniques. The ultra-dense scenario will become more and more common with the rising urbanization rate. According to the United Nations, 54 percent of the world's population lives in urban areas, this proportion is expected to increase to 66 percent by 2050 [3].

In addition to the device density, the provisioning of diverse IoT services is another major challenge to the IoT network in the future. With the developing of Artificial Intelligence (AI) technique, it is expected to be widely implemented in IoT network in the future[4]. AI technique provides smart IoT devices more capacity to judge and comprehend the environment based on sensed or gathered information, and allows smart IoT devices to operate more personalized and diverse IoT services. On the one hand, AI can be adopted to manage and schedule the ultra-dense deployed IoT networks [5]; On the other hand, most of the AI techniques require enormous of data or cases for environment sensing and machine-learning model training [6, 7]. Meanwhile, the ultra-dense deployed IoT network has high capability to generate data for AI. According to the industrial report from Cisco, IoT devices will generate more than 847 zettabytes (10^{21}) data by 2021 [8]. Supported by the data generated in the IoT networks, AI operated on each device are able to generate their personalized transmission demand the enhance the IoT service experience.

Currently, there are many existing wireless communication techniques. While according to Cisco, the percentage of Wi-Fi (Wireless Fidelity) transmission will keep increasing and reach 63 percent of total transmission by 2021. Wi-Fi is playing an "expanding role" to facilitate the upcoming IoT era [9], while it also face so challenges such diversity of QoS requirements and ultra-dense deployment in future IoT network, as is shown in Figure 1.1.

Figure 1.1: Evolving Wi-Fi design objectives for better wireless communication in the future.

Since the Institute of Electrical and Electronics Engineers Standards Association (IEEE-SA) initiated the wireless local area network (WLAN) standard - IEEE 802.4L in 1988, the IEEE WLAN standard has evolved over 30 years [10]. In 1990, this standard was firstly renamed as IEEE 802.11, which is also called Wi-Fi nowadays. The first "legacy" IEEE standard 802.11 was published in 1997, supported by direct-sequence spread spectrum (DSSS) technique with maximum 2 Mbps data rate working at 2.4GHz. The DSSS was improved in 802.11b with 11Mbps data rate [11]. In 2003, IEEE 802.11g standard firstly adopted Orthogonal frequency-division multiplexing (OFDM) at 2.4 GHz with maximal 54Mbps data rate. Even though the OFDM was firstly adopted at 5GHz in IEEE 802.11a in 1999, it is not widely adopted because of the shorter transmission range [12, 13]. In the 802.11n, which is published in 2009, the multiple-input multiple-output (MIMO) antennas technique is firstly included, the maximum data rate is extended to 600Mbps as well [14]. In 802.11ac, the Multi-user MIMO (MU-MIMO) is adopted in the Wi-Fi [15], this version standard also provides a boarder bandwidth (80MHz), more spatial stream and higher level of modulation scheme (256-QAM) [16, 17]. These features improve the maximum data rate of 802.11ac to 1300Mbps [18]. In 2014, the High Efficiency WLAN (HEW) task group start working on the next generation WLAN standard, IEEE 802.11ax, which aims at supporting at least 4 times improvement in the average throughput in dense deployment scenarios [19, 20].

1.2 Thesis Motivations

Even though the IEEE 802.11 standard has developed near 20 years and the 802.11ax proposed new features for more flexible resource allocation and more efficient access in ultra-dense network, there are still two existing challenges.

One challenge is the ultra-dense deployment of Wi-Fi stations (STAs). Even though the next generation Wi-Fi standard 802.11ax involves new PHY layer technique, Orthogonal Frequency Division Multiple Access (OFDMA), to improve the ultra-dense networks performance and flexibility to serve diverse transmission requirements. Nevertheless, the ultra-dense performance of 802.11 ax still degrades as STAs number rises, which is further explained in Section 3.2.

The other challenge is the increasing diversity of transmission demands due to the rising number of IoT devices and more applications of IoT services, such as Industry 4.0 [21], smart city [22], smart home [23], smart advertising [24] and so on. Different services have different quality of service (QoS) performance requirements. In conventional system design, the QoS enhancement force more on the particular performance indicator, such as throughput, latency, reliability, etc. However, these absolute value of QoS performance may not properly express the true experience of services. For instance, communication for both industrial control and live video stream have high requirement on latency[21, 25]. In the industrial control area, the high latency cannot be tolerated because the delay of control information may cause serious loss, the importance of latency is higher than other performance when evaluating the transmission experience, or we can say the communication for industrial control prefers the latency more. While in the transmission of live video stream, both throughput and latency are important to the transmission experience, their importance is similar. If we regard these two services as the same, normalize the sum of the "weight factor" of all requirement for each service, and allow each service freely allocates the "weight factor" to different QoS performance, the latency weight factor of industrial control should be higher than the weight of live video stream, even if they have the same latency requirement. This difference leads to different results in network access and resource allocation. Therefore, considering diverse IoT services operated on massive IoT devices, how to properly schedule the access and resource allocation in the ultra-dense network with different QoS performance becomes a meaningful topic.

In order to address these two challenges, a more adaptive Wi-Fi access and resource allocation scheme is required.

1.3 Research Objectives

In order to address the challenges of the upcoming IoT era, including the system and STA performance in ultra-dense network and the diverse QoS requirement, this thesis are mitigating these challenges with following sub-objectives:

Maintaining the RU efficiency and throughput in ultra-dense network: The IEEE 802.11ax standard adopts OFDMA in PHY layer to enhance the ultra-dense network performance. By dividing channels into smaller sub-channels, called resource units (RUs), OFDMA allows Access Points (APs) simultaneously access multi-users (MUs) in one channel and flexibly allocate these RUs to satisfy diverse demands of user devices. However, due to the high collision rate in the ultra-dense network, the performance of existing access mechanism in 802.11ax still decreases. Uwai et al. and Lanante et al. proposed proposed and simplified an adaptive backoff-parameter adjusting mechanism to optimize the throughput and channel efficiency [26], [27], based on the number of access STAs. But the performance of this mechanism still declines in the ultra-dense network, which will be illustrated in Section 3.2. Therefore, the first objective of this thesis is that proposing a scheme to ease the influence of collision in random access and maintain the system performance of Uplink (UL) MU access mechanism of 802.11ax in the ultra-dense network.

Improve the Utility of QoS from different users with different requirement: Generally different IoT devices have different requirement of QoS performance, as is mentioned in section 1.2. This thesis describes different requirements of these QoS performances by "weight factor", which is involved in the "QoS Utility" function to numerically evaluate the transmission experience. Note that the "utility" is widely adopted to describe the performance of both overall system and each user in the network with multiple services [28], [29]. In this thesis, we use the latency as the example to value the utility of QoS in 802.11ax, and propose a new hybrid scheme to further improve the utility of latency in the ultra-dense network of 802.11ax.

1.4 Technical Contributions of the Thesis

In this thesis, an adaptive Uplink OFDMA Random Access (UORA) grouping scheme is proposed at first, based on the analyzed function relationship between RU utilize efficiency and STA number, including their closed-form expression and two propositions. By adaptively adjusting the number of simultaneous access STA along the time domain, the proposed scheme effectively copes with the high collision problem and maintains the optimal performance of UORA in the ultra-dense networks. Furthermore, an adaptive UORA grouping algorithm is proposed to cope with the performance fluctuation due to remainder STAs after grouping. In the adaptive UORA grouping algorithm, the adaptive grouping range is derived by the analyzed function relationship between channel efficiency and STA number. By diminish the influence of remainder STAs, the RU utilize efficiency and throughput of adaptive grouping scheme are much higher than conventional UORA in the ultra-dense network.

Due to the low efficiency of random access, we also study the performance of adaptive grouping scheme in the BSR-based two-stage mechanism (BTM), which reserves the advantages of UORA as well as maintains the channel efficiency. The relationship between system performance of BTM and STA number is analyzed. The numerical results present that the throughput of adaptive BTM grouping scheme has 2.55, 413.02 and 3712.04 times gains compared with the UORA grouping, conventional BTM and conventional UORA, respectively.

Not only the normal performance indexes are considered, we also propose a hybrid BTM grouping scheme with both random and scheduled access mechanism to improve the QoS performance and STA utility. The latency is selected as an example and studied. The utility function is used to value the STA utility. A group allocation scheme for hybrid BTM is analyzed with the functional relationship. Considering different dimensions of environment features, the numerical results demonstrate that the hybrid BTM grouping scheme has much better QoS performance than conventional method.

1.5 Thesis Outline

The rest of this thesis is organized as follows:

Chapter 2 introduces some new features of 802.11ax in both PHY and MAC layers involved in this thesis;

In Chapter 3, the relationship between the system performance of UORA and STA number is studied, a grouping UORA scheme is proposed to ease the high collision rate in the ultra-dense networks. Meanwhile, an adaptive group size grouping scheme is proposed to address the performance fluctuation after grouping. The performance of proposed grouping scheme is evaluated by the numerical results;

The property of BTM is studied and the proposed grouping scheme is adopted in BTM to enhance the performance, which is also evaluated by the numerical results in 4.

In Chapter 5, we propose and study a Hybrid BTM Grouping scheme, which allows STAs access in either random or scheduled scheme. In order to provide better QoS experience in the ultra-dense network with diverse IoT services, we proposed a Hybrid BTM Grouping algorithm to guarantee the QoS requirement from high priority STAs. The performance of proposed scheme is evaluated by the numerical results with different dimensions of performances and considering diverse factors that influence these performances.

Chapter 6 concludes the works of this thesis and illustrate some possible research directions in the future.

Chapter 2

Operation Principle of IEEE 802.11ax

2.1 Overview

The wide application of IoT and the increasing number of IoT devices lead to more deployment of dense wireless networks. The growing rate of urbanization and limited range of urban area will further exacerbate the conflict between limited communication capability of current wireless standard and increasing demand of ultra-dense networks. Therefore, the High-Efficiency WLAN (HEW) task group is working on the next generation WLAN standard, IEEE 802.11ax, which was approved by the IEEE-SA in 2014. The scope of the IEEE 802.11ax is to “enable at least at least four times improvement in the average throughput per station (measured at the MAC data service access point) in a dense deployment scenario, while maintaining or improving the power efficiency per station” [20]. In order to achieve this s-cope, IEEE 802.11ax firstly includes several new features like Orthogonal Frequency-Division Multiple Access (OFDMA), trigger frame, UORA and target wake time (TWT) and so on [30].

Meanwhile, a new control frame, ”trigger frame”, is proposed in the IEEE 802.11ax MAC layer, in order to synchronize and control the access of MU. Trigger frame contains the resource allocation information for multiple STAs access and the standard also defines the operation rules after STAs received the trigger frame. As the de-facto random access mechanism, UORA is one of these rules for MU transmission. UORA is defined as a trigger-based random access mechanism for MU UL transmission in IEEE 802.11ax, which is initialized and synchronized by a trigger frame, and utilizes random access as the contention mechanism [30]. Even though the efficiency of UORA is not high and also influenced by STAs number, it can be directly adopted for MU access when AP has no information about these STAs, which is suitable for information soliciting before data transmission, or data transmission in the dynamic network. Here the “dynamic” means STAs leave and join the network frequently [31]. For more efficient access and resource allocation in the ultra-dense networks with diverse demand of STAs, it is better to schedule the resource allocation scheme after solicited reliable information about following transmission. Therefore, IEEE 802.11ax defines Buffer Status Report (BSR) frame to carry the status information in each STA's buffer. The buffer of each STA storages the pending package for transmission. BSR frame is sent from STA to AP, which contains the QoS label and the size of the following data frames from each STA. The transmission of BSR frame indicates that this STA has data frames to transmit, AP can schedule the resource allocation for accessed STA based on this and information in the BSR frame. Even though some details of operation rules have not been decided yet, the basic principle of BSR mechanism is clear. The AP solicits the BSR frames from STAs through UORA mechanism at first, then the AP responses the resource allocation scheme to accessed STA and receives the data frames from these STAs without contention.

The details of these features will be introduced in the following subsections one by one. Because this thesis forces on the UL transmission in the ultra-dense networks, the rest new features of IEEE 802.11ax will not be included in the following chapters.

2.2 Physical Layer of IEEE 802.11ax

2.2.1 Overview

IEEE 802.11ax firstly adopts the OFDMA as Physical (PHY) layer technique. In the conventional OFDM system, one OFDM symbol is assigned to one STA. In the OFDMA system, the OFDM symbol is divided into smaller blocks and can be assigned to multiple STA simultaneously [32], which also leads to several remarkable changes in the PHY layer of IEEE 802.11ax. The rest of this section will introduce: The details of OFDMA; The minimal unit that can be allocated to one STA, Resource Unit (RU); The modulation and coding scheme in

OFDMA; The PHY data packet operated on the OFDMA.

2.2.2 Orthogonal Frequency-Division Multiple Access (OFDMA)

Orthogonal Frequency-Division Multiple Access (OFDMA) is an OFDM-based multiple access scheme. Similar to the widely used OFDM technique in conventional versions of 802.11 standard, the OFDMA also employs multiple subcarriers. But OFDMA furtherly divides each subcarrier into multiple smaller subchannel, called Resource Unit (RU). Comparing with conventional OFDM, adopting OFDMA allows the access point (AP) simultaneously supports UL or downlink (DL) MU transmission, which reduces the preamble and channel access overhead. Meanwhile, the smaller sub-channel bandwidth provides higher flexibility for granularized resource allocation and diverse QoS provisioning in IoT networks. The difference between OFDM with OFDMA is illustrated in Figure 2.1.

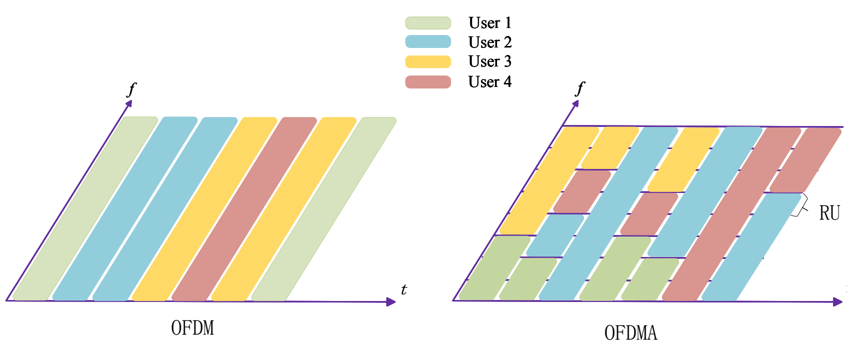

Figure 2.1: Typical applications of wireless sensor networks.

As is shown in Figure 2.1, in conventional OFDM, each subcarrier can only access one user in one time slot, while the OFDMA can access multiple users simultaneously. Because in OFDMA, the channel is divided into several RUs in the frequency domain, AP can allocate these RUs to different users in one time slot to achieve function of multi-user access.

2.2.3 Resource Unit (RU) Types in OFDMA

In IEEE 802.11ax, the minimal subcarrier bandwidth is 78.125kHz, which is called “tone” in the standard [30]. In order to satisfy diverse transmission demand in the ultra-dense network, 802.11ax defines different types of RU, which contains different number of tones, including 26, 52, 106, 242, 484, 996 or 2x996 tones. Meanwhile, compared with legacy 802.11 standard, 802.11ax supports wider bandwidth choice including 20, 40, 80, 80+80 and 160MHz. The allocation of different types of RU is shown in Figure 2.2-2.4.

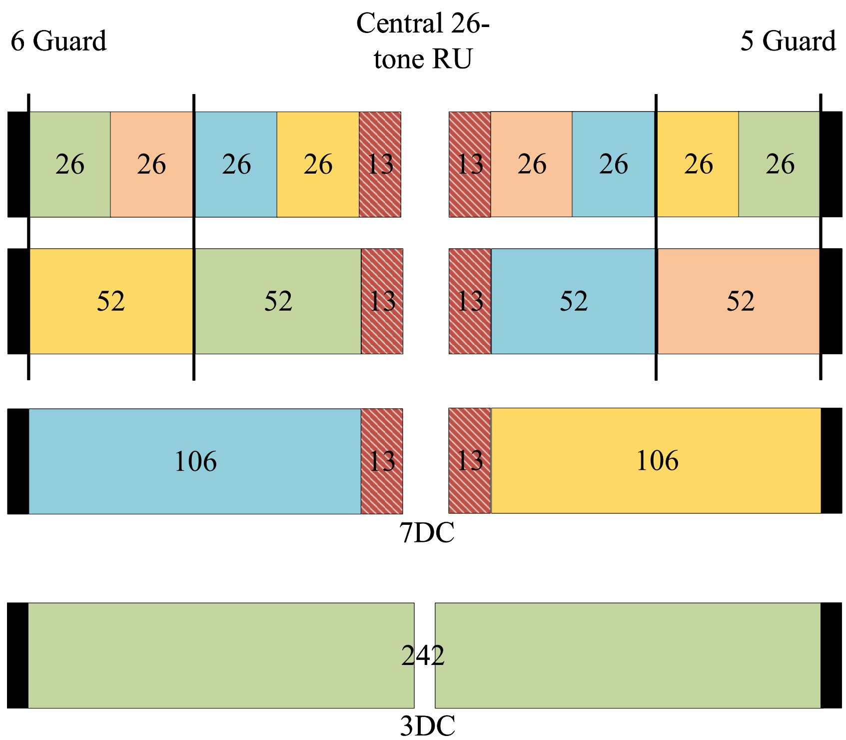

Figure 2.2: RU types in 20 MHz channel.

As is shown in Figure 2.2-2.4, the RU allocation in different bandwidth channel is illustrated. For instance, a 20MHz channel can contain nine 26-tone RUs, or four 52-tone RUs with one 26-tone RU, or two 106-tone RU with one 26-tone RU, or one 242-tone RU. The maximum number of RUs allocation in different bandwidth's channel is presented in Table 2.12.1. In this thesis, we are studying an ultra deployed of the IoT network, the data payload is not high and the network is expected to support as many users as possible. Meanwhile, the preamble is duplicated in each 20 MHz subchannel within the transmission band [33]. Therefore, we only consider a single 20MHz channel with 9 of 26-tone RUs in this thesis.

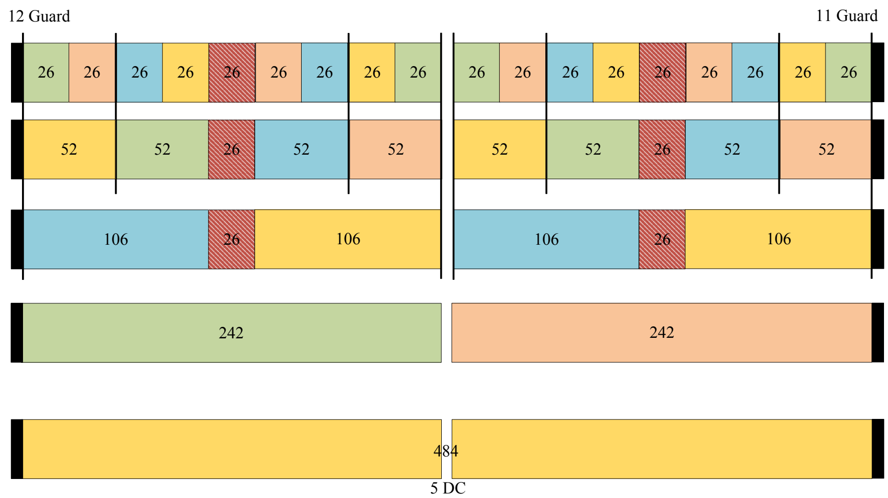

Figure 2.3: RU types in 40 MHz channel

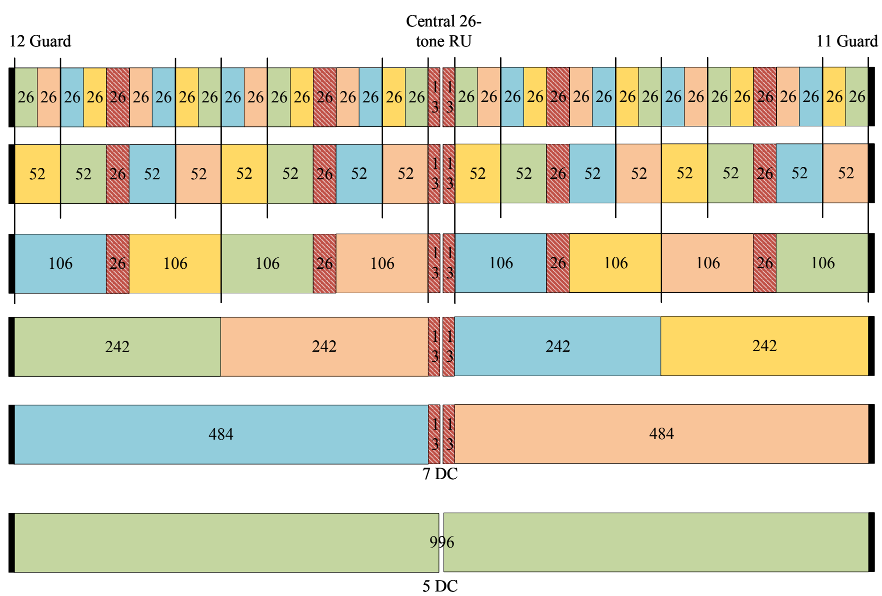

Figure 2.4: RU types in 80 MHz channel

Table 2.1: Maximum RU number for each channel

RU type	**20MHz**	**40MHz**	**80MHz**	**160(80+80)MHz**
26-tone	9	18	37	74
52-tone	4^{+1}	8^{+2}	16^{+5}	32^{+10}
106-tone	2^{+1}	4^{+2}	8^{+5}	16^{+10}
242-tone	1	2	4^{+1}	8^{+2}
484-tone	N/A	1	2^{+1}	4^{+2}
996-tone	N/A	N/A	1	2
2*996-tone	N/A	N/A	N/A	1

2.2.4 Modulation and Coding Scheme of OFDMA

The Modulation and Coding Scheme (MCS) index reflects the information of modulation, coding [18]. In conventional 802.11, devices in the network can dynamically adjust the index of MCS based on the channel status. The MCS index range from 0-9, which represent the modulation scheme including BPSK, QPSK, 16-QAM, 64-QAM, and 256-QAM and the coding rate including 1/2, 2/3, 3/4, and 5/6. When the communication channel has high Signal Noise Ratio (SNR), AP or STAs can choose high MCS index for higher transmission data rate. But if the channel condition is not good, such as high fading rate, high level of interference or noise, AP or STAs may choose lower MCS index to increase the transmission reliability. The transmission of some management frame or control frames will also choose low MCS, in order to improve the reliability of these critical transmissions.

The following table 2.2 shows who MCS index define the modulation scheme and coding rate in conventional 802.11 standard [18]. The conventional 802.11 standard support maximal MCS 9, which adopting 256-QAM and 5/6 coding rate. 802.11ax firstly extend the MCS index to 10 and 11, which is represent adopting 1024-QAM modulation scheme with 3/4 and 5/6 coding rate respectively. But MCS 10 and 11 only available in the RU that has 242 tones or more [30]. In this thesis we only consider 26-tone RU in 20MHz bandwidth channel, which maximally supports MCS 9.

Table 2.2: MCS index and its represented modulation and coding scheme

MCS index	Modulation	Coding rate
0	BPSK	1/2
1	QPSK	1/2
2	QPSK	3/4
3	16-QAM	1/2
4	16-QAM	3/4
5	64-QAM	2/3
6	64-QAM	3/4
7	64-QAM	5/6
8	256-QAM	3/4
9	256-QAM	5/6
10	1024-QAM	3/4
11	1024-QAM	5/6

2.2.5 Format of Physical Layer Data Packet in IEEE 802.11ax

The High-Efficiency trigger-based Presentation Protocol Data Unit (HE TB PPDU) is one type of the High-Efficiency PPDU proposed in the IEEE 802.11ax, which is adopted for uplink data transmission in through the RU. In conventional 802.11 standard, the data packet for Physical Layer Convergence Procedure (PLCP) is called Presentation Protocol Data Unit (PPDU). However, in 802.11ax, due to the application of OFDMA, channel is divided into several RUs. In order to support the new feature, there are several types of new PPDUs presented in 802.11ax for different transmission mechanism, such as the data frame for single-user, multiuser, and extended range transmissions scenarios [19]. In this thesis, we will focus on the HE trigger-based PPDU (HE TB PPDU). The HE TB PPDU is mostly used for UL MU data transmission, which is transmitted as the response of a Trigger Frame. The format of HE TB PPDU is presented in Figure. 2.5.

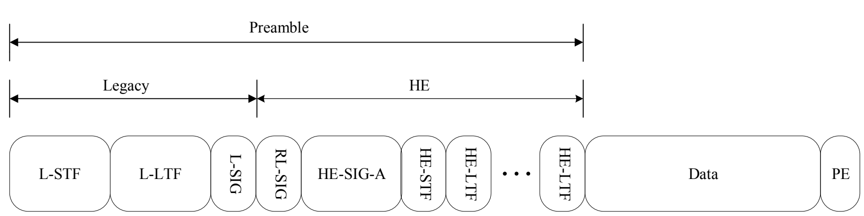

Figure 2.5: Format of HE TB PPDU

The L-STF, L-LTF, L-SIG fields are legacy PHY preamble, and the RL-SIG, HE-SIG-A, HE-STF and HE-LTF are HE preamble for 802.11ax. In the data field of HE TB PPDU, there is a PLCP Service Data Unit (PSDU), which is also the MAC Protocol Data Unit (MPDU). The structure of MPDU will be introduced in the next subsection.

2.3 MAC of IEEE 802.11ax

Medium access control (MAC) sublayer is part of the data link layer, which mainly responses to control the channel access and data transmission. In 802.11ax, the major function of MAC layer includes: queuing management, access control, carrier sensing control, frame control, resource scheduling and transmission control [34]. This section will mainly introduce two parts of MAC layer of 802.11ax, including the format of MAC frame and some access mechanisms presented in this thesis.

2.3.1 MAC Frame Format

Generally, a frame in MAC layer contains three basic parts: a MAC header, a length-variable frame body and a Frame Check Sequence (FCS). The MAC frame format of is shown as Figure. 2.6

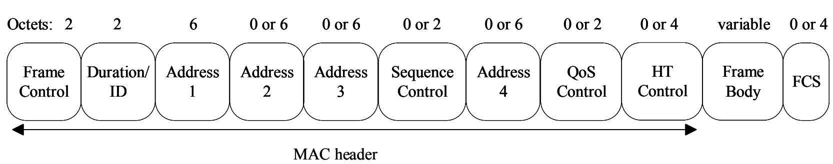

Figure 2.6: MAC frame format of IEEE 802.11ax

In the MAC header, the basic control information is presented in the Frame Control subfield. The Frame Control subfield presents the information such as the protocol version, type of the frame, the frame transmitter and receiver and so on. There are majorly four types of the frame in 802.11 standard, including management frame, control frame, data frame and extension frame. These frame types are defined by Type subfield in the Frame Control subfield.

More specifically, the particular frame type is defined by the Subtype subfield in the Frame Control subfield. The details of frame types and its definition is illustrated in Table 2.3.

Note that Trigger frame is the new frame defined in 802.11ax.The system model of this thesis will involve the frames including:

1) Management frame :

   Beacon frame

2) Control frame:

   Trigger frame

   Muti-BlockAck frame (one type of BlockAck frame)

3) Data frame:

   QoS Data frame (included in the HE TB PPDU for data transmission)

   QoS Null frame (used for Buffer Status Report)

The details of these frame structures will be illustrated in the following subsection and the application of these frames will be presented in the Section 2.3.2.

2.3.1.1 Trigger Frame

Trigger frame is a control frame sent by access point (AP) to STAs. By requiring S-TAs to response a frame after they received the trigger frame waiting for a short inter-frame space (SIFS). Trigger frame provides a time synchronization for distributed UL transmission from multiple STAs [35]. The application of trigger frame also simplifies the MU resource allocation process in WLAN, and facilitates to achieve improved network efficiency and reliability, compared to the conventional carrier-sense multiple access with collision avoidance (CSMA/CA) mechanism. A trigger frame contains information for allocation the following parallel HE TB PPDU transmissions in a channel. The transmissions of HE TB PPDU wait for a SIFS after STAs received the trigger frame. The frame structure of trigger frame is presented in the Figure 2.7.

Table 2.3: Combinations of type and subtype

Type value	Type description	Subtype value	Subtype description
00	Management	0000	Association Request
00	Management	0001	Association Response
00	Management	0010	Reassociation Request
00	Management	0011	Reassociation Response
00	Management	0100	Probe Request
00	Management	0101	Probe Response
00	Management	0110	Timing Advertisement
00	Management	0111	Reserved
00	Management	1000	Beacon
00	Management	1001	ATIM
00	Management	1010	Disassociation
00	Management	1011	Authentication
00	Management	1100	Deauthentication
00	Management	1101	Action
00	Management	1110	Action No Ack
00	Management	1111	Reserved
01	Control	0000–0001	Reserved
01	Control	0010	Trigger[802.11*ax*]
01	Control	0011	TACK[802.11*ah*]
01	Control	0100	Beamforming Report Poll
01	Control	0101	VHT/HE NDP Announcement
01	Control	0110	Control Frame Extension
01	Control	0111	Control Wrapper
01	Control	1000	Block Ack Request (BlockAckReq)
01	Control	1001	Block Ack (BlockAck)
01	Control	1010	PS-Poll
01	Control	1011	RTS
01	Control	1100	CTS
01	Control	1101	Ack
01	Control	1110	CF-End
01	Control	1111	CF-End +CF-Ack
10	Data	0000	Data
10	Data	0001	Data +CF-Ack
10	Data	0010	Data +CF-Poll
10	Data	0011	Data +CF-Ack +CF-Poll
10	Data	0100	Null (no data)
10	Data	0101	CF-Ack (no data)
10	Data	0110	CF-Poll (no data)
10	Data	0111	CF-Ack +CF-Poll (no data)

Table 2.3 Combinations of type and subtype (Continue)

Type value	Type description	Subtype value	Subtype description
10	Data	1000	QoS Data
10	Data	1001	QoS Data +CF-Ack
10	Data	1010	QoS Data +CF-Poll
10	Data	1011	QoS Data +CF-Ack +CF-Poll
10	Data	1100	QoS Null (no data)
10	Data	1101	Reserved
10	Data	1110	QoS CF-Poll (no data)
10	Data	1111	QoS CF-Ack +CF-Poll (no data)
11	Extension	0000	DMG Beacon
11	Extension	0001–1111	Reserved

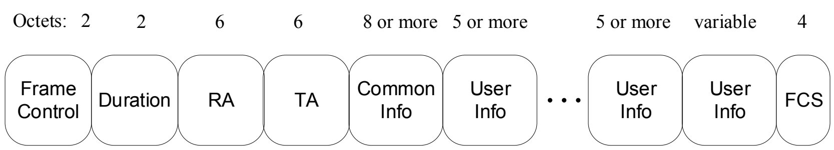

Figure 2.7: Trigger frame format

There are two majority changes in the trigger frame compared with conventional control frame. First is the Common information field, this field defines some common information of this trigger frame and the transmission in the channel. The details structure of common information field is shown in Figure 2.8.

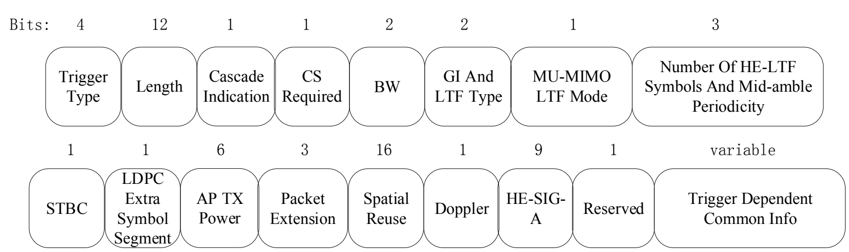

Figure 2.8: Format of Common information field

As is shown in the Figure 2.8, this field contains the basic information for this trigger frame and state of following transmission in this channel, including the type and length of this trigger, bandwidth, Guard interval, transmission power of AP, MU-MIMO, spatial reuse and so on.

There are several types of trigger frame designed for different transmission scenarios, STAs will prepare different frames to response the trigger frame according to the type of the received trigger frame. The valid types of trigger frame are shown in the following Table 2.4. In

Table 2.4: Valid type of trigger frame

Trigger Type subfield value	**Trigger frame variant**
0	Basic
1	Beamforming Report Poll (BRP)
2	MU-BAR
3	MU-RTS
4	Buffer Status Report Poll (BSRP)
5	GCR MU-BAR
6	Bandwidth Query Report Poll (BQRP)
7	NDP Feedback Report Poll (NFRP)
8-15	Reserved

this thesis, we will use two types of trigger frames. One is the basic trigger frame designed for soliciting HE TB PPDU transmissions, the other one is the Buffer Status Report Poll Trigger frame (BSRP-TF), which is designed for soliciting the BSR frame. The details of BSR frame and relative mechanism will be illustrated in Section 2.3.3, and the application of BSR frame is illustrated in Chapter 4.

The second difference is the User information field, which contains the allocation scheme and necessary PHY layer information for transmission in the following RUs. There are one or more user information fields in each trigger frame, depends on the number of accessed users, but no more than the number of maximum RUs in the channel. The frame structure of User Information Field is shown in Figure 2.9.

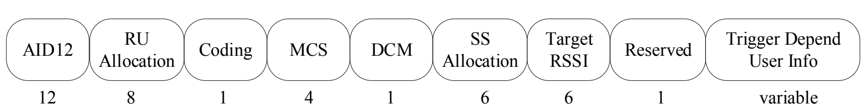

Figure 2.9: Format of User information field

As is shown in Figure 2.9, in the user information field there is a 12 bits AID subfield that indicates the Least significant bit (LSB) of the STA' s AID, and the RU allocation subfield indicates the RU used by the HE TB PPDU of the STA that is identified by previews AID subfield.

Containing several user information fields, trigger frame can schedule the access scheme of MU, which will be illustrated in Section 2.3.4.

2.3.1.2 Multi-BlockAck Frame

The Mutil-BlockAck (M-BA) frame is a new subtype of BlockAck frame proposed in the 802.11ax. M-BA aggregates multiple users' acknowledge information, which indicates whether the previous transmission is successful or not. Generally, an M-BA frame is sent from AP to multiple STAs after UL MU transmission of HE TB PPDUs. The structure of BlockAck is shown in Figure 2.10.

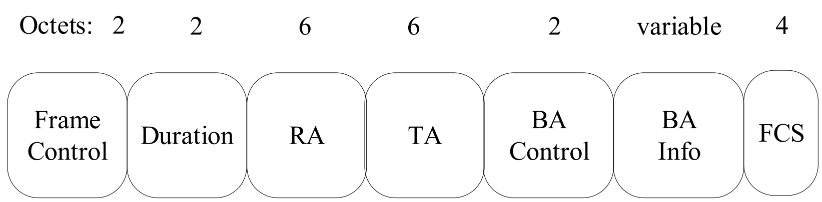

Figure 2.10: Format of Block Acknowledge frame

The subtype of BlockAck frame is presented in the BA Control subfield, and the relative acknowledge information is presented in the BA information field. The BA control field is shown in Figure 2.11.

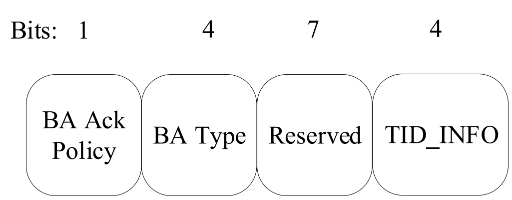

Figure 2.11: Format of BA control field

In Figure 2.11, the type of the BlockAck frame is defined in the BA Type subfield, the definition of BA Type subfield and the valid types of BlockAck frame are presented in the Table 2.5.

Table 2.5: BA Type definition and valid type of BlockAck frame

BA Type	**BlockAck frame variant**
0000	Basic BlockAck
0001	Reserved
0010	Reserved
0011	Reserved
0100	Compressed BlockAck
0101	GLK-GCR BlockAck
0110	GCR BlockAck
0111	Reserved
1000	Extended Compressed BlockAck
1001	Reserved
1010	Reserved
1011	Reserved
1100	Multi-TID BlockAck
1101	Multi-STA BlockAck
1110	Reserved
1111	Reserved

Note that Multi-STA BlockAck(M-BA) is the new type defined in IEEE 802.11ax. In the Table. 2.5, there are many Reserved Bits due to undecided transmission mechanism, such as the BTM. According to [31], there are maybe two possible M-BA frames in the BTM, one is that M-BA contains the information subfield which has the similar function as Trigger Frame, the other is the conventional M-BA frame. The details of BTM will be illustrated in Chapter 4.

Expect the reserve bits, there are still many types of BlockAck frame in the Table. 2.5, each type of M-BA has their own format of BA information subfield. In this subsection, we will focus and illustrated the BA information subfield format of M-BA, which is presented in the Figure 2.12.

As is shown in the Figure 2.12, there are multiple per AID TID information subfield in the BA information, one per AID TID information subfield corresponds to one STA. Each per AID TID information subfield contains one AID TID Info subfield and two optional subfields. In AID TID Info subfield there are three subfields included: AID11, Ack Type and TID subfields. The AID11 subfield carries the 11 LSBs of the AID, which indicates the previous transmission

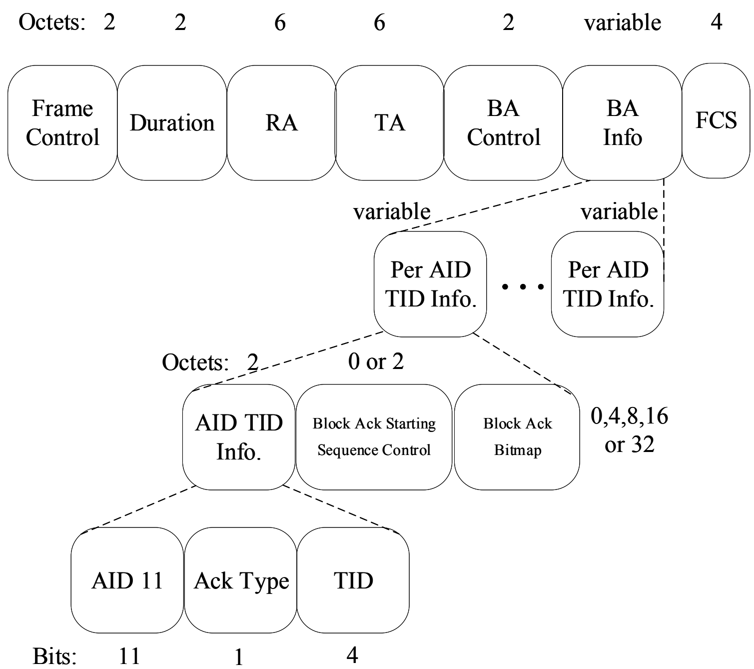

Figure 2.12: Format of BA control field

of this STA is received. The Ack Type indicates whether there is a aggregation in the MPDU of previous transmission. The TID is used to support QoS for higher layer's entity.

2.3.1.3 QoS Null Frame and BSR Control

This section will illustrate that how QoS Null Frame contains the BSR information by presenting and explaining the details of frame structure. The function and application of BSR are presented in Section 2.3.2.2.

Generally, in all frame defined in 802.11, there is an optional sequence control information field, called HT control field in the MAC header [18]. The Mac frame format is shown as Figure 2.6. In order to support the transmission of BSR, STA needs to use the QoS Null Data frame, the frame type definition is presented in Section 2.3.1. Meanwhile, STA needs to apply the optimal HT control field which carries BSR information. The first two bits in the HT control field indicate the structure of the subtype of this HT control field. The structure of HT control field is shown in Figure 2.13-2.15.

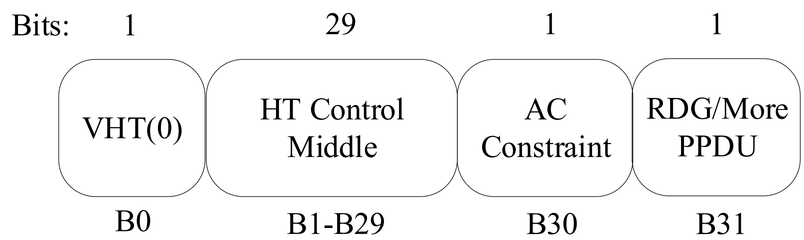

Figure 2.13: Format of HT variant

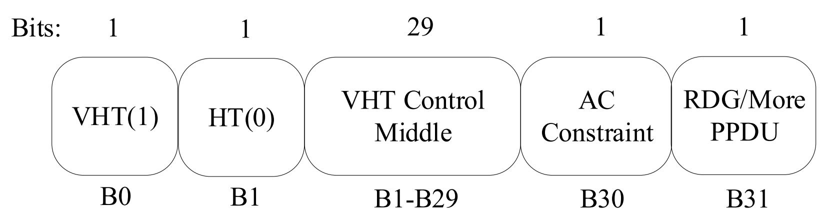

Figure 2.14: Format of VHT variant

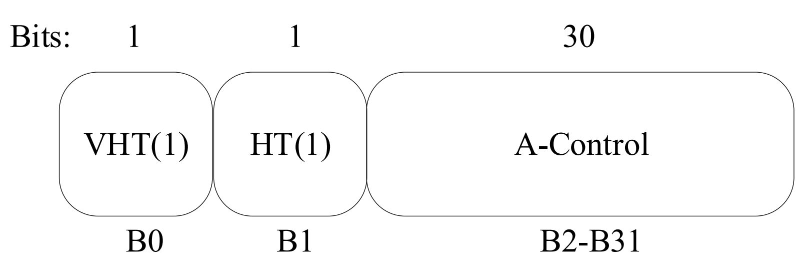

Figure 2.15: Format of HE variant

The HT Control field has three forms, note that the HE variant is a new type defined in 802.11ax, which carries the BSR information is in the Aggregated control (A-control) subfield. The format of A-control subfield is presented in the Figure 2.16.

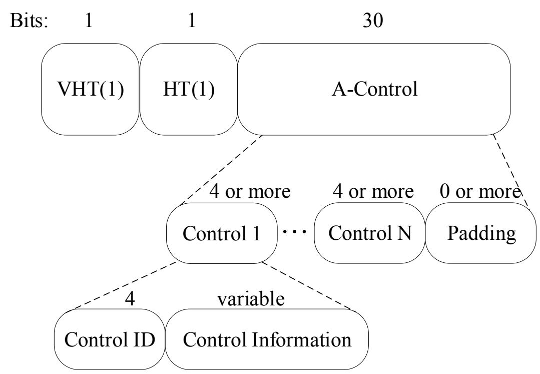

Figure 2.16: Format of A-control subfield

A-control subfield contains one or more control subfield, and the total length of the A-control subfield is equal to 30 bits. There are several types of control subfield, which is defined by the control ID subfield as is shown in Figure 2.16. The length and details of control information are variable according to the control type. The structure of each control subfield is presented as Table 2.6.

Table 2.6: Control ID subfield

Control ID	**Meaning of control ID**	**Length of the Control Info. subfield**
0	UL MU response scheduling (UMRS)	26
1	Operating mode (OM)	12
2	HE link adaptation (HLA)	26
3	Buffer status report (BSR)	26
4	UL power headroom (UPH)	8
5	Bandwidth query report (BQR)	10
6	Command and status(CAS)	8
7-15	Reserved	

Currently, there are 7 types of different control subfield as is shown in the Table. 2.6, when control ID equals to 3, the Buffer Status Report is included. The length its control information subfield is 26 bits, which means there is only one control subfield in the A-control subfield (length of A-control field is limited by 30 bits). The structure of control information subfield is presented in Figure 2.17.

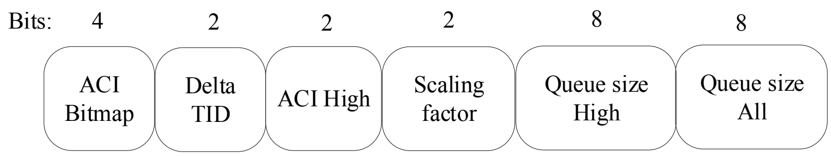

Figure 2.17: Format of BSR informaiton subfield

In the control information subfield for BSR, ACI bitmap, Delta TID and ACI High indicate the QoS status of the queues in buffer, the Scaling Factor, Queue Size High, and Queue Size All indicate the Queue size in the buffer. Note that the ACI High indicate the ACI of Queue Size High subfields, and Queue Size All indicates all queues size in the buffer.

With the BSR from each STA, AP can properly schedule the access and resource allocation for a more efficient network. Section 2.3.2 will briefly introduce the access mechanism of Chapter 4 and 5 will present the application of BSR to improve the system performance.

2.3.2 MAC Mechanism

2.3.2.1 Uplink OFDMA Random Access (UORA)

Different from the conventional 802.11, which mainly adopts the CSMA/CA mechanism for access control. In 802.11ax, several new MU access techniques are proposed. Uplink OFDMA Random Access (UORA) is designed as the de-facto random access mechanism for UL MU transmission, considering its ability that UORA can initialize a transmission without pre-schedule information, which is also adopted to support pre-scheduled transmission as well. The details of UORA are illustrated in the following paragraphs.

UORA is a trigger-based random access mechanism for MU UL transmission that is initialized and synchronized by a trigger frame. Utilizing random access as the contention mechanism for resource allocation among multiple users, this process does not require any pre-scheduling information for transmission and provides a parallel access method for MUs. Generally, one full UORA process includes three parts of frame transmission:

- Process initialization by the trigger frame broadcasted from AP;
- STAs response the corresponding frames according to the information of previews trigger;
- AP feedback a Multi-BlockAck after it received at least one frame from STAs.

In the trigger frame, AP can either schedule the allocation of RUs or set RUs for random access. When AID12 subfield equal to the 12 LSBs of the AID of the STA, this RU is assigned to this STA. Otherwise, if the AID12 subfield equal to 0, this RU is allocated for associated STAs RA. And if AID12 subfield equal to 2045, this RU is allocated for unassociated STAs RA. An example of UORA mechanism is shown in Figure 2.18.

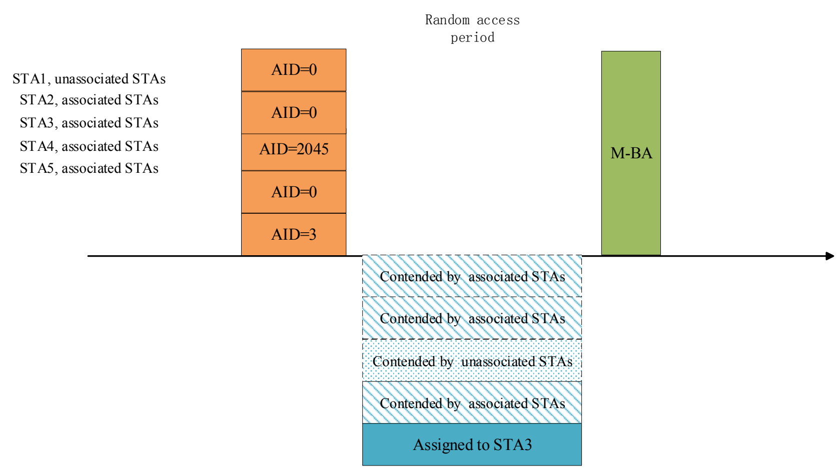

Figure 2.18: An example of the UORA mechanism.

In Figure 2.18, RU1, RU2, and RU4 are assigned for Random Access (RA), STAs that support RA might content these RUs after backoff. RU3 is assigned to unassociated STAs, the unassociated STAs can access the network through this RU and establish the connection with AP. RU5 is assigned to STA3, which is scheduled by AP based on previous information feedback from STA3 or other reliable information that indicates STA3 will transmit in this time slot.

In order to avoid the collision of directly access the RU for Random Access (RA-RU), 802.11ax designs an OFDMA backoff (OBO) process. After STAs received the trigger frame from AP, if these STAs are not assigned RU and in the trigger frame there are user information field has the subfield whose AID equals to 0 or 2045, STA will STAs start OBO process. Each STA has an OBO counter to storage the backoff status. If the OBO counter value of one STA is equal or lower than 0, it will randomly access one RA-RU. After STAs successfully access and transmit their data, AP will respond with a Multi-BlockAck (MBA) and mention these STAs.

The details of OBO process are illustrated as follow: firstly, one STA sets up the OBO counter by minimal and maximal OFDMA contention window (OCW), denoted as OCW_{min},OCW_{max} respectively. Their values are derived from $EOCW_{min}$ and $EOCW_{max}$ field in Random Access Parameter Set (RAPS) element of the beacon frame, the frame structure of RAPS element is illustrated in Figure 2.19.

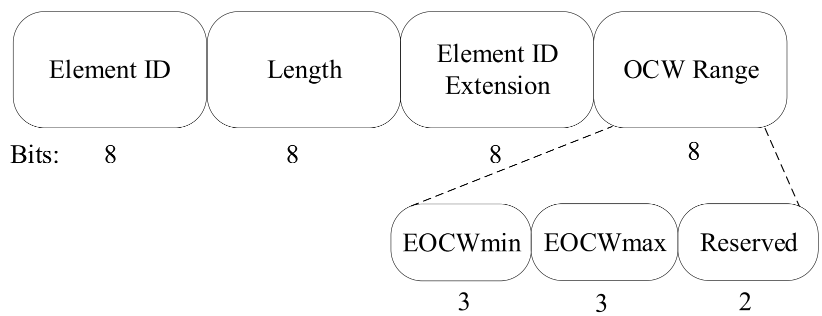

Figure 2.19: The format of RAPS element in Beacon frame

With given $EOCW_{min}$ and $EOCW_{max}$, the parameters OCW_{min}, OCW_{max} and the maximal backoff stage m, are calculated, respectively, as:

$$OCW_{min} = 2^{EOCW_{min}} - 1, \tag{2.1}$$

$$OCW_{max} = 2^{EOCW_{max}} - 1, \tag{2.2}$$

$$m = EOCW_{max} - EOCW_{min}. \tag{2.3}$$

The OBO counter is initialized in $[0, OCW_{min}]$. After the STA receives trigger frame from AP, its OBO counter subtracts the number of RA-RUs, which is indicated in the trigger frame. If the value of OBO counter is equal or lower than 0, this STA will randomly choose one of the

RA-RUs to access. If two or more STAs access the same RU, the collision happens. The OBO counters of these STAs will double the OCW and reset the OBO counter based on new OCW. If this STA accesses the RA-RU without collision, the OBO counters will be reset using initial OCW value. If the OBO counter value is higher than 0, the counter will retain this value until the next trigger frame comes.

The OBO counters of collision STAs will double the old OCW (OCW_{old}) and reset the OBO counter based on new OCW (OCW_{new}), but the OCW_{new} should not be higher than OCW_{max}.

$$OCW_{new} = 2 * (OCW_{old} + 1) - 1, \quad OCW_{new} \leq OCW_{max} \tag{2.4}$$

$$OCW_{new} = OCW_{max}, \quad OCW_{new} > OCW_{max} \tag{2.5}$$

$$OBO = i, \forall i \in [0, OCW_{new}] \tag{2.6}$$

If this STA accesses the RA-RU without collision, the OBO counters will be reset in the range from 0 to the initial OCW value, OCW_{min}. If the OBO counter value is higher than 0, STA will not transmit, and the counter will retain this value until the next trigger frame comes. Note that the principle of OBO process is similar to conventional back-off process in CSMA/CA mechanism, while there is no waiting time when reduce the value of OBO counter.

Once the STA received the trigger frame, it directly subtracts OBO counter value by the number of RA-RU, so there is no time loss when backoff. After one STA successfully go through the OBO process, it will transmit the corresponding frame according to the type of the trigger frame. For instance, STA while response HE TB PPDU if it receives a basic trigger frame, this process is a conventional UL data transmission process. If it receives the BSRP trigger frame, will response BSR frame, this is an information soliciting process, which will be further illustrated in Chapter 4, and the details of BSR frame is presented in Section 2.3.5.

2.3.2.2 Buffer Status Report (BSR)-based Mechanism

Buffer Status Reports (BSRs) mechanism is an information soliciting mechanism to assist AP to schedule the transmission in allocating UL MU resources, STAs can report their BSRs without requirement from AP, and AP can also solicit the STAs’ reports about the queue size and QoS label in their buffer. There are two types of BSR, for unsolicited BSR, STAs can transmit BSRs that are contained in the QoS Control field or BSR Control field of any frame transmitted from STA to the AP, for solicited BSR, STAs can deliver BSRs in QoS Null frame that is sent to the AP as the response of a BSRP-TF. In this thesis, we will focus on the solicited BSR.

In the solicited BSR, AP sends a BSRP-TF to initiate and synchronize the BSR mechanism, then STAs, who received the BSRP-TF and prepared to UL transmission, will report the queue frame size and QoS label in their buffer, though the QoS Null frames. The transmission process of BSR mechanism is similar to the conventional UORA mechanism, which is illustrated in Figure 2.20.

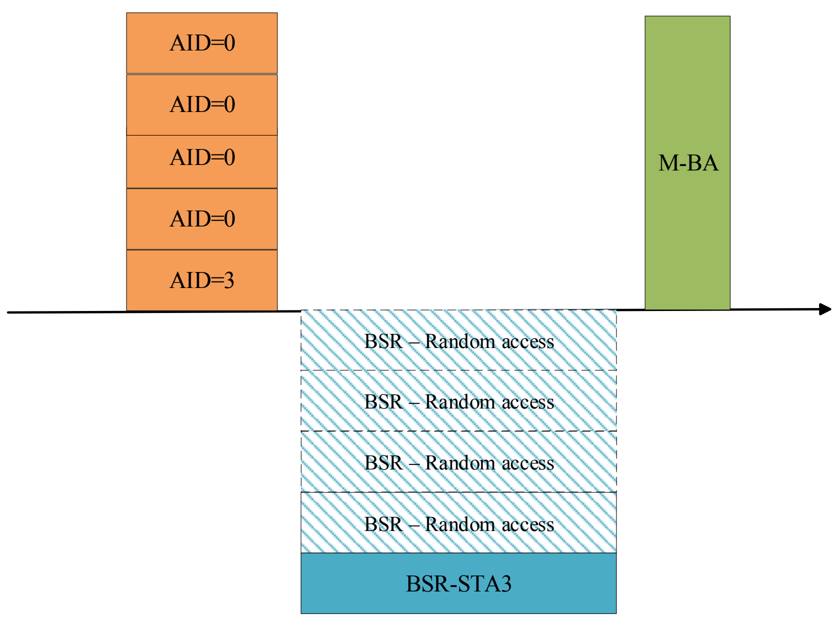

Figure 2.20: An example of BSR transmission.

Generally, in solicited BSR mechanism, AP waits for a DIFS after the last transmission, and then broadcasts a BSRP-TF to all STAs in this channel to initial the BSR mechanism. When STAs receive the BSRP-TF, if their buffers are not empty and these STAs support UO-RA mechanism, they will response QoS Null frames that contain their BSRs to AP following UORA mechanism according to the allocation scheme in the trigger frame. For instance, as is shown in figure 2.20, BSRP-TF allocates RU5 to STA3 to transmit its BSR, and assigns RU1-4 for random access, the rest STA in this channel need to contend the access of these RUs to transmit their BSRs. The details of UORA contention process is illustrated in Chapter 2.3.4. After AP received at least one BSR from these STAs, it transmits an M-BA frame.

After the transmission of BSR, there will be a contention free data transmission process, the detail of this process is presented in Chapter 4.

2.3.2.3 Target Wake Time Mechanism

Target Wake Time (TWT) is a WLAN STAs grouping mechanism in the time domain for power saving and collision easing, which is firstly proposed in IEEE 802.11ah and also included in the IEEE 802.11ax [30, 36].

In general TWT mechanism, STAs will negotiate the wake up time with AP at first, then wake up at the negotiated time point to start transmission, this negotiation enables AP to schedule the access scheme before the data transmission, which is more efficient than conventional CSMA/CA. In the negotiating period, there are two valid mechanisms, one is the Individual TWT agreement, which allows STAs to individually negotiate with AP. This agreement provides more flexibility for STAs about the wake up time, but it requires lots of time to negotiate the wake up time one by one before transmission. Meanwhile, the maximum number of simultaneously active agreements is limited to 8, which will highly degrades the network performance in the ultra-dense deployed scenario.

Therefore, 802.11ax proposes a new mechanism for TWT negotiation in the ultra-dense network, called Broadcast TWT operation. Different from Individual TWT agreement, it is not necessary for STAs to negotiate the wake up time with AP one by one. AP can directly broadcast TWT parameters to STAs without the individual agreements between AP and STAs, but STAs still need to negotiate the membership with AP [30].

Compared with the conventional Individual TWT agreement, the STAs do not have the freedom to choose the TWT parameters in Broadcast TWT operation, but they have the choice to whether take part into this transmission or not. With the given TWT parameters from AP, the negotiation process is much simpler than Individual TWT agreement, which also allows the AP supporting more number of STAs in the TWT mechanism in the ultra-dense network.

This thesis focus on the ultra-dense network, therefore we assume that the Broadcast

TWT operation is the default negotiation mechanism of TWT mechanism in the rest part of this thesis.

There is the scheduled data transmission period after the negotiation process. In this period, because AP scheduled all TWT parameters, STAs only wake up in the scheduled wake up time for transmission, called TWT Service Periods (SPs). In the other time outside the SP, STA will turn into doze state, which saves the power of STAs as well as the channel resources of the network [26, 37]. During the SP, STA and AP can either do UL or DL transmission, including the access mechanism mentioned in Section 2.3.2.2 and 2.3.2.1.

In order to support the TWT scheduling for large scale of STA access, there is also a TWT grouping mechanism. In this mechanism, AP can add STAs into TWT groups and then scheduled the access of the whole group of STAs. Compared with the conventional TWT mechanism, one of the differences of TWT grouping in negotiation process is that AP needs to transmit an individually addressed frame to STA [36]. This frame will include a TWT element which contains the TWT group ID assigned this STA and the TWT parameters for this group. In the data transmission period after negotiation, the access principle of TWT grouping is similar to the conventional TWT mechanism. All STAs in each group will follow the TWT parameters scheduled by AP, and only wake up in the scheduled SP, STAs in this group will turn into doze state outside the SP for this group.

The TWT grouping mechanism can be used to divide STAs into several groups in the time domain, and ease the contention such as the UORA mention in the previous section, the details will be illustrated in the next chapter.

2.4 Summary of the Chapter

In this chapter, fundamental aspects of 802.11ax that will be considered in this thesis are introduced, including the PHY and MAC layer features. In the PHY layer, the adoption of OFDMA divides channels into multiple RUs, which improves the MU access ability as well as the resource allocation flexibility. In the MAC layer, we mainly introduced the frame structure and access mechanism that will be studied in this thesis. The Trigger frame and BSR are firstly adopted in 802.11ax, which provides better access control and resource allocation for transmission. Meanwhile, the UORA, BSR-based two-stage and TWT mechanism were introduced, which will be further illustrated in the rest of this thesis.

Chapter 3

UORA Analysis and Proposed Adaptive UORA Grouping Scheme

3.1 Overview

UORA is a trigger-based random access mechanism for UL MU transmission. This mechanism adopts random access for resource allocation among multiple STAs, which does not require any pre-scheduling information for transmission and provides a parallel access method for MU access and transmission. Therefore, UORA is suitable for information soliciting before data transmission or directly user for data transmission when it is difficult for AP to receive the pre-scheduling information.

As the de-facto random access mechanism, UORA directly influences the system performance in IEEE 802.11ax. It attracts high attentions of researchers. The authors in [38] firstly studied the UORA system using bi-dimensional Markov chain in 2016. However, the accuracy of this model is limited because of the early version of the draft standard. This model was improved in [39], while the results are complex. Then a simple form with accurate analysis model of UORA was derived in [40]. Unfortunately, one of the significant problems of UORA, according to [38, 39, 40], is the degrading efficiency caused by high collision probability in the ultra-dense networks. The adaptive backoff mechanism proposed in [39, 26], tries to maintain the optimal system efficiency by extending the contention windows. However, in IEEE 802.11ax, the maximal backoff window in UORA is 127. It leads to the result that the adaptive backoff mechanism cannot be adopted in the scenario with a large number of STAs.

To conquer these drawbacks, we propose an adaptive UORA grouping scheme based on the TWT grouping mechanism. The grouping strategy has already been widely used in wireless communication to eliminate the collision [41], improve the resource allocation [42, 43], Energy scheduling [44] and so on.

In our proposed scheme, STAs are divided into several groups along the time dimension to eliminate the collisions. In order to optimize the system efficiency as well as eliminate the influence of remainder when grouping, an adaptive grouping algorithm is designed to facilitate AP grouping STAs.

The the rest of this chapter is organized as follows: Section 3.2 analyzes and illustrates the existing and potential problem of UORA in the ultra-dense network; The system model of proposed UORA grouping scheme is formulated in Section 3.3; In Section 3.4, the relationship between STAs number with RU efficiency is studied, and the optimal group size is derived; Section 3.5 proposes an adaptive grouping algorithm based on the results of adaptive group size, which ease the performance fluctuation after grouping; The performance of proposed algorithm is evaluated by numerical results in Section 3.6; Section 3.7 summarizes the works of Chapter 3.

3.2 Challenges of UORA in Ultra-Dense Deployment

As is mentioned in Section 2.3.2.1, UORA is a random access mechanism. Similar to the conventional CSMA/CA, the collision rate of UORA still rise as STAs number increases. The relationship between STAs number with collision rate of UORA is presented in Figure 3.1.

The collision rate rises sharply when the STA number increases and approach to 1 when STA number arrives around 140. Some researchers proposed an adaptive backoff mechanism to maintain the optimal system efficiency by extending the contention windows. But this method only has limited functions. Because the maximum value of EOCWmax is 7, the maximum value of OCWmin and OCWmax equals to $2^7 - 1 = 127$. This backoff window in much shorter than the value in conventional standard. The performance with different backoff parameters is shown in Figure 3.2.

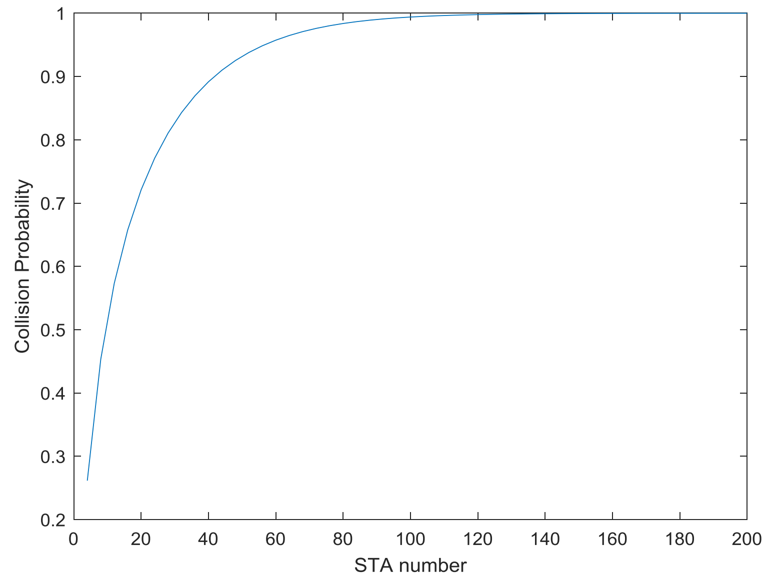

Figure 3.1: Rising collision rate with increasing STA number.

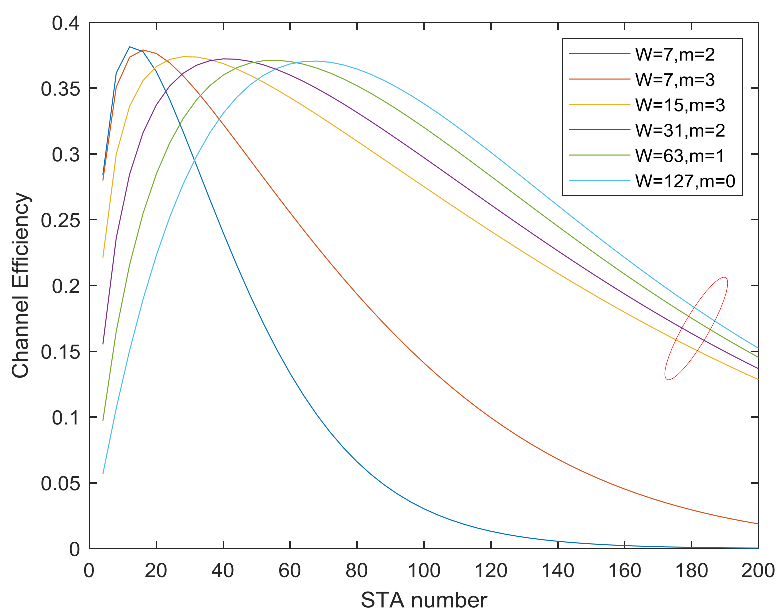

Figure 3.2: The limitation of adaptive parameter adjust optimization.

The maximum active range of this algorithm is $n = 67$, when the parameters are set to "W=127, m=0 and r=9" in a 20MHz channel. The performance of RU efficiency still degrades when STA number is higher than 67. One available method is extending the backoff windows, but it will raise the power consumption of each STA. Therefore, a more effective access scheme is necessary to be proposed to solve this problem.

3.3 System Model and Formulation of UORA Grouping Scheme

This thesis considers an ultra-dense IEEE 802.11ax network with single AP and n STAs accessing the network through the proposed UORA grouping mechanism, which is operated through the following procedures.

The AP first assigns all STAs to different groups using TWT mechanism. After the grouping process, all STAs listen to the beacon frame from AP. Once they receive the beacon frame, STAs turn into doze state until their TWT SPs come. During each TWT SP, STAs wake up to receive the trigger frame sent by AP, then STAs compete for the RUs using the UORA mechanism. After the transmission in the TWT SP, STAs in the group turn into doze state until their next TWT SP. The proposed grouping scheme is illustrated in the Figure 3.3, where STAs are divided into G groups, each group stays in doze state until their TWT SP.

Several assumptions are made to simplify the subsequent analysis. The PHY layer is assumed to be ideal with no transmission error, while the network is saturated. All STAs are associated with the AP with equal access priority. All analysis and simulation results are in the steady-state after the grouping and group adaptation processes. The notations used in this paper are summarized in Table 3.1.

In the rest part of this paper, the OCW_{min} is represented by W_0, the OBO parameters represent r, W_0 and m. The parameters proposed for adaptive grouping range, α, N_{rmin} and N_{rmax}, are introduced in the next section.

Since STAs are divided into several groups using different TWT SPs in the time domain, their transmissions are independent. The proposed scheme can be considered as several successive and independent UORA processes. Hence, it is necessary to analyze the UORA process, so as to evaluate and optimize the performance of the proposed scheme.

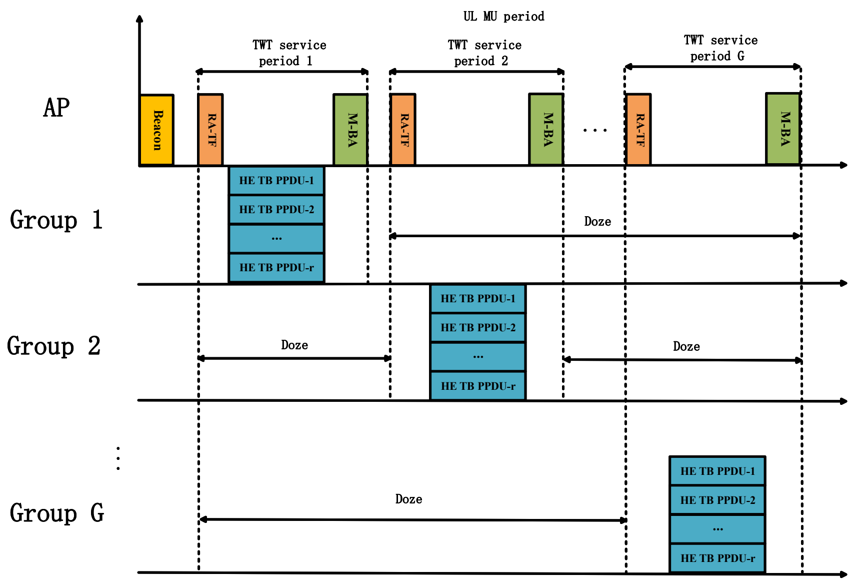

Figure 3.3: UORA grouping scheme based on TWT grouping mechanism.

Table 3.1: Parameter definition

Parameter	**Meaning**
n:	STA number
r:	Number of RU
$OCW_{min}(W_0)$:	Minimal contention window size
i:	i-th backoff stages
m:	Maximum number of backoff stages
p:	Collision possibility
η:	Efficiency of RU
τ:	Transmit probability
α:	Efficiency factor
N_{rmin}	Lower bound of group size
N_{rmax}	Upper bound of group size
G:	Total group number
j:	j-th group
N_j:	STA number in the j-th group
η_j:	RU efficiency the j-th group
H:	Efficiency of UORA grouping scheme

According to the analysis of conventional UORA process in [40], the probability τ that one STA sends out the messages after OBO is expressed as:

$$\tau = \frac{W_0 + 1}{W_0 + 1 + (1-p)X_0 + (1-p)\sum_{i=1}^{m-1} X_i(\frac{p}{2})^i + X_m(\frac{p}{2})^m}, \tag{3.1}$$

where

$$X_i = (-\frac{r}{2}\left\lfloor\frac{W_i}{r}\right\rfloor^2 + (W_i - \frac{r}{2})\left\lfloor\frac{W_i}{r}\right\rfloor),$$

and

$$W_i = 2^i(W_0 + 1) - 1, i \in [1, m-1].$$

Meanwhile, the STAs randomly choose the available RU to access the AP, the probability p that collision happens in the chosen RU can be derived as [40]:

$$p = 1 - (1 - \frac{\tau}{r})^{n-1}. \tag{3.2}$$

Because the STAs randomly choose the RU, when study one RU, the queue model should be M/G/1, therefore the utilization efficiency of each RU can be derived as [40]:

$$\eta(p) = \frac{n\tau(1-p)}{r}. \tag{3.3}$$

As is shown in (3.1)-(3.3), the efficiency of RU is influenced by OBO parameters and STA number n. The UORA grouping scheme is supposed to improve the system performance in the ultra-dense network by reducing the access number of STA each time. The grouping strategy is directly impacted by n, which is studied in the next section with given OBO parameters.

3.4 Derivation of Optimal Group Size

In order to achieve optimal grouping, the closed-form expression of maximized RU efficiency is derived as a function of station number and OBO parameters in this section. Meanwhile, the monotonicity of the efficiency function is proved. The variable range of group size is analyzed so as to provide more flexibility grouping method to cope with remainder problem.

By substituting the equation (3.2) into (3.3), the efficiency function of p can be rewritten as:

$$\eta(p) = n(1-(1-p)^{\frac{1}{n-1}})(1-p). \tag{3.4}$$

Proposition 1: The maximal efficiency of RU (3.4) is reached when:

$$n(1-p)^{\frac{1}{n-1}} - n + 1 = 0, n \in [2, \infty), p \in [0, 1]. \tag{3.5}$$

Proof By regarding n as constant, the first order of $\eta(p)$ is calculated as:

$$\frac{\mathrm{d}\eta(p)}{\mathrm{d}p} = \frac{n}{n-1}(n(1-p)^{\frac{1}{n-1}} - n + 1). \tag{3.6}$$

Suppose $Z_1 = n(1-p)^{\frac{1}{n-1}} - n + 1$, the first order derivative of Z_1 is:

$$\frac{\mathrm{d}Z_1}{\mathrm{d}p} = \frac{-n(1-p)^{\frac{1}{n-1}}}{(n-1)(1-p)} < 0. \tag{3.7}$$

By substituting (3.7) in to (3.6), it is obvious that $\frac{\mathrm{d}\eta(p)^2}{\mathrm{d}^2p} < 0$. Therefore, for any $n \geq 2$, the η reaches maximal when $Z_1 = 0$, the constrain is expressed as:

$$n(1-p)^{\frac{1}{n-1}} - n + 1 = 0. \tag{3.8}$$

■

According to (3.1), (3.3) and (3.5), the RU efficiency is maximized when it follows the constrains (3.9), which is a close-form expression that only contain the n and OBO parameters.

$$\frac{W_0+1}{W_0+1+(1-\frac{1}{n})^{n-1}\sum_{i=0}^{m-1}X_i(\frac{1-(1-\frac{1}{n})^{n-1}}{2})^i + X_m(\frac{1-(1-\frac{1}{n})^{n-1}}{2})^m} - \frac{r}{n} = 0, n \in [2, \infty) \tag{3.9}$$

$$\eta_{opt} = (1 - \frac{1}{N_{opt}})^{N_{opt}-1}. \tag{3.10}$$

$$\begin{cases} \alpha\eta_{opt} = n(1-(1-p)^{\frac{1}{n-1}})(1-p) \\ \frac{W_0+1}{W_0+1+(1-p)\sum_{i=0}^{m-1}X_i(\frac{p}{2})^i+X_m(\frac{p}{2})^m} - r(1-(1-p)^{\frac{1}{n-1}}) = 0 \end{cases}, n \in [2, \infty), p \in [0, 1] \tag{3.11}$$

By regarding OBO parameters as given constants, the optimal group size N_{opt} can be calculated using numerical method. According to (3.4) and (3.9), the optimal result of efficiency can be derived as (3.10). Generally, when grouping the STAs, the total STA number can not be exactly divided by the N_{opt} without remainder. If the remainder is small, directly allocating few STAs into one TWT SP may waste the channel resource. Therefore, the efficiency factor $\alpha \in [0, 1]$ is proposed, which provides more flexibility in grouping by sacrificing $(1-\alpha)\eta_{opt}$ of RU efficiency. According to (3.4), (3.9) and (3.10), the variable range of group size can be calculated by (3.11).

Proposition 2: If $n < N_{opt}$, the efficiency of RU (3.4) is monotone and increasing; If $n > N_{opt}$, (3.4) is monotone and decreasing.

Proof The proof of Proposition 2 is presented in this section. By substituting the calculated N_{opt} in to (3.8), this equation can be rewritten as:

$$1 - p^{opt} = (1 - \frac{1}{N_{opt}})^{N_{opt}-1}. \tag{3.12}$$

Suppose $n < N_{opt}$. According to (3.2), it is easy to prove that $p(n)$ is a monotone and increasing function. Thus $p < p^{opt}$ is true. The function Z_1 is constrained by:

$$\begin{aligned} Z_1 =& n(1-p)^{\frac{1}{n-1}} - n + 1 \\ >& n(1-p^{opt})^{\frac{1}{n-1}} - n + 1 \\ =& n((1-p^{opt})^{\frac{1}{n-1}} - (1 - \frac{1}{n})), \end{aligned} \tag{3.13}$$

According to (3.12), the final term of (3.13) can be rewritten as:

$$n((1-p^{opt})^{\frac{1}{n-1}} - (1 - \frac{1}{n})) = n(1 - \frac{1}{N_{opt}})^{\frac{N_{opt}-1}{n-1}} - (1 - \frac{1}{n}). \tag{3.14}$$

According to assumption $n < N_{opt}$, because $1 - \frac{1}{N_{opt}} \in (0, 1)$, it is easy to prove that

$$(1 - \frac{1}{N_{opt}})^{\frac{N_{opt}-1}{n-1}} - (1 - \frac{1}{n}) > 0. \tag{3.15}$$

By substituting (3.15) into (3.13), the first order $\frac{\mathrm{d}\eta(p)}{\mathrm{d}p} > 0$ is proved. The monotony of $\eta(p)$

when $n > N_{opt}$ can be proved in the similar method.

■

According to Proposition 2, n has one or two roots in (3.11). Supposed the smaller root is N_{rmin} and the bigger root is N_{rmax}. If there is only one root, this root is N_{rmax} and $N_{rmin} = 2$. The variable range of group size is expressed as $[N_{rmin}, N_{rmax}]$. Therefore, when the group size of each group $N_j \in [N_{rmin}, N_{rmax}]$, the RU efficiency of each group $\eta_j \in \left[\alpha\eta_{opt}, \eta_{opt}\right]$.

3.5 Proposed Adaptive Grouping Algorithm

In this section, we proposed an adaptive grouping algorithm based on the analysis results of optimal group size and variable range of group size.

The proposed algorithm improves the system efficiency as well as eliminate the remainder problem, by using variable range of group size $N_j \in [N_{rmin}, N_{rmax}]$ to divide STAs adaptively. The proposed adaptive grouping algorithm is shown in Algorithm 1.

If the total STA number n is higher than N_{opt}, the algorithm will firstly try to use N_{opt} as the object to divide STAs into $G = \left\lfloor \frac{n}{N_{opt}} \right\rfloor + 1$ groups. Every group has N_{opt} STAs except the last group, which has $n \mod N_{opt}$ STAs. Then the algorithm checks the value of the remainder $n \mod N_{opt}$, if it is lower than N_{rmin}, it will cancel the last group and divide the last group equally into other groups.

After this reallocation process, if there are still at least one group has more than N_{rmax} STAs, the algorithm will try to generate more groups by using N_{rmin} rather than N_{opt} as the object to divide STAs, and repeat the operation described in the previous paragraph. With the output of the algorithm G and N_j, the RU efficiency of each group after grouping can be expressed as:

$$\eta_j(p) = N_j(1 - (1 - p_j)^{\frac{1}{N_j - 1}})(1 - p_j), \ j \in [1, G] . \tag{3.16}$$

The average efficiency of the system can be derived as:

$$H(p) = \frac{1}{G}\sum_{j=1}^{G} \eta_j(p). \tag{3.17}$$

In some cases, if the variable grouping range is small, the output if the algorithm N_j may not allocate in the range, this problem will be discussed in the next section.

Algorithm 1: Adaptive grouping algorithm

Input: N_{opt},N_{min},N_{max},n
Output: G, N_j,$\forall j \in [1, G]$

if $n > N_{opt}$ **then**
  $G \Leftarrow \left\lfloor \frac{n}{N_{opt}} \right\rfloor + 1$
  for $j \in [1, G-1]$ **do**
    $N_j \Leftarrow N_{opt}$
  $N_G \Leftarrow n \mod G$
  if $N_G < N_{rmin}$ **then**
    $G \Leftarrow \left\lfloor \frac{n}{N_{opt}} \right\rfloor$
    for $j \in [1, G]$ **do**
      if $j \in [1, (n \mod G) \mod G]$ **then**
        $N_j \Leftarrow N_{opt} + \left\lfloor \frac{n \mod G}{G} \right\rfloor + 1$
      else
        $N_j \Leftarrow N_{opt} + \left\lfloor \frac{n \mod G}{G} \right\rfloor$
    if $N_j > N_{rmax}, \forall j \in [1, G]$ **then**
      $G \Leftarrow \left\lfloor \frac{n}{N_{rmin}} \right\rfloor + 1$
      for $j \in [1, G-1]$ **do**
        $N_j \Leftarrow N_{rmin}$
      $N_G \Leftarrow n \mod G$
      if $N_G < N_{rmin}$ **then**
        $G \Leftarrow \left\lfloor \frac{n}{N_{rmin}} \right\rfloor$
        for $j \in [1, G]$ **do**
          if $j \in [1, (n \mod G) \mod G]$ **then**
            $N_j \Leftarrow N_{rmin} + \left\lfloor \frac{n \mod G}{G} \right\rfloor + 1$
          else
            $N_j \Leftarrow N_{rmin} + \left\lfloor \frac{n \mod G}{G} \right\rfloor$

3.6 Performance Evaluation

In this section. The efficiency improvement of proposed grouping scheme is presented, comparing with the conventional UORA and adaptive backoff mechanism. The influence of efficiency factor α on the proposed algorithm performance is studied as well. The throughput improvements of both system and single STA are presented. All of the OBO parameters in this section is assumed as follows: $r = 9$, considering 20MHz bandwidth; $m_0 = 2, W_0 = 7$, which are default setting in the standard [30].

3.6.1 RU Efficiency

The RU efficiency performance of the adaptive grouping algorithm is shown in Figure 3.4, comparing with conventional UORA and adaptive backoff mechanism proposed in [27]. When STA number is small, the parameter optimization algorithm has higher RU efficiency, by reducing unnecessary RUs for random access. However, its RU efficiency still decreases when $n > 67$ because of the length limitation of $EOCW_{max}$ in the RAPS element of Beacon frame. Compared with UORA and parameter optimization algorithm, the grouping algorithm maintains the high performance that approaches to the optimal result.

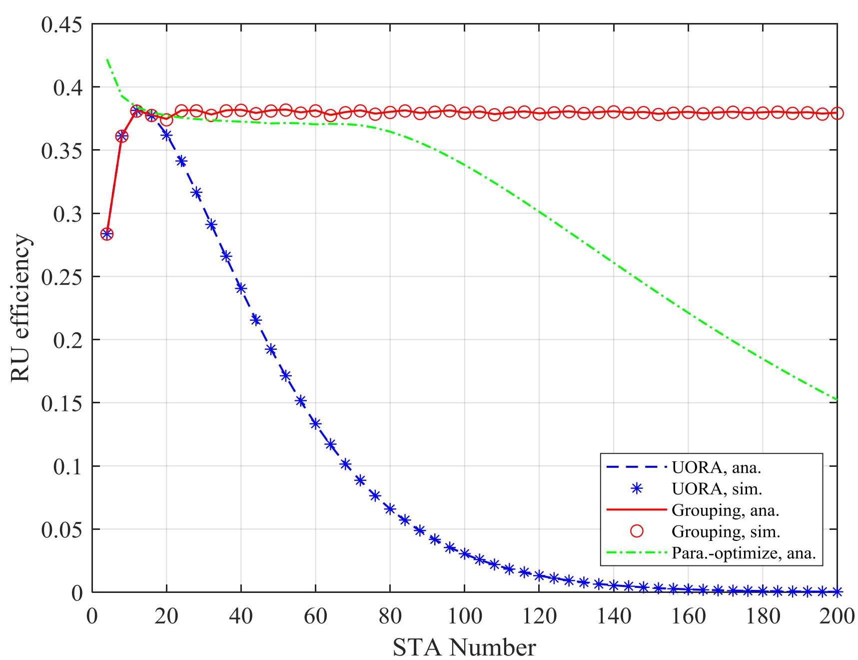

Figure 3.4: RU efficiency of adaptive grouping algorithm compared with conventional UORA and adaptive backoff mechanism.

3.6.2 Impact of Efficiency Factor α

The efficiency factor α offers the AP more flexibility to group the STAs and minimize the impact of remainder stations in UORA grouping. However, when the variable grouping range is small, the performance can't be exactly guaranteed in $\left[\alpha\eta_{opt}, \eta_{opt}\right]$. The performance of different α selection is presented in Figure 3.5. As is shown in Figure 3.5, if the variable range is too tight, such as $\alpha = 1$, it is difficult for algorithm to guarantee that all groups have N_j STAs in the range. If the variable range is too loose, such as $\alpha = 0.5$, the performance will decrease as well. Though N_j can all allocate in the range, the design performance $\alpha\eta$ is far away from the η_{opt}. Therefore, it is necessary to consider both of these two factors when selecting the α.

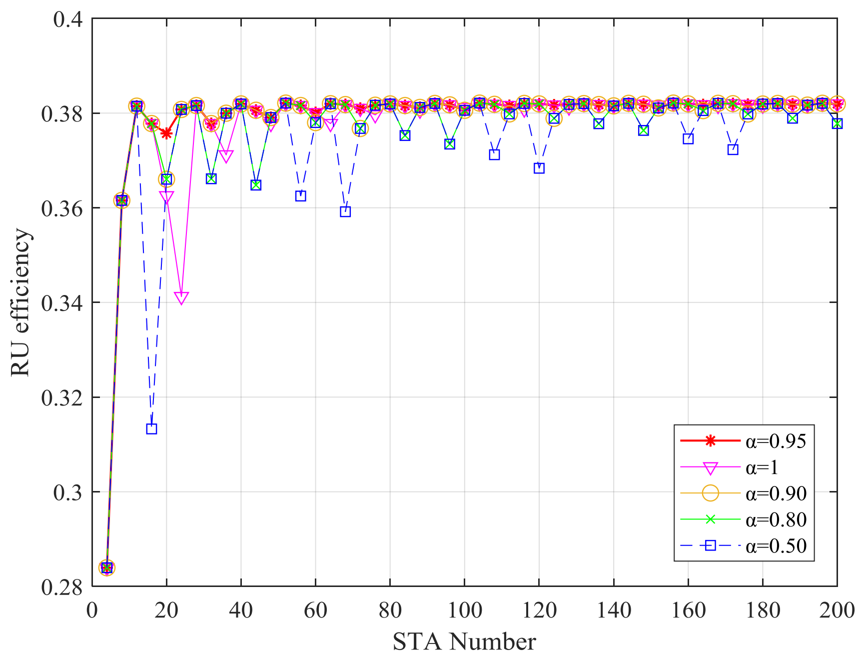

Figure 3.5: RU efficiency with different factor α selection.

The proposed adaptive grouping has the near optimal performance as is shown in the Figure 3.6. Here, the certain group means the AP divides STAs into certain number of groups despite how many STAs in each group. The proposed adaptive grouping algorithm (red line) cuts the optimal performance of each certain groups line.

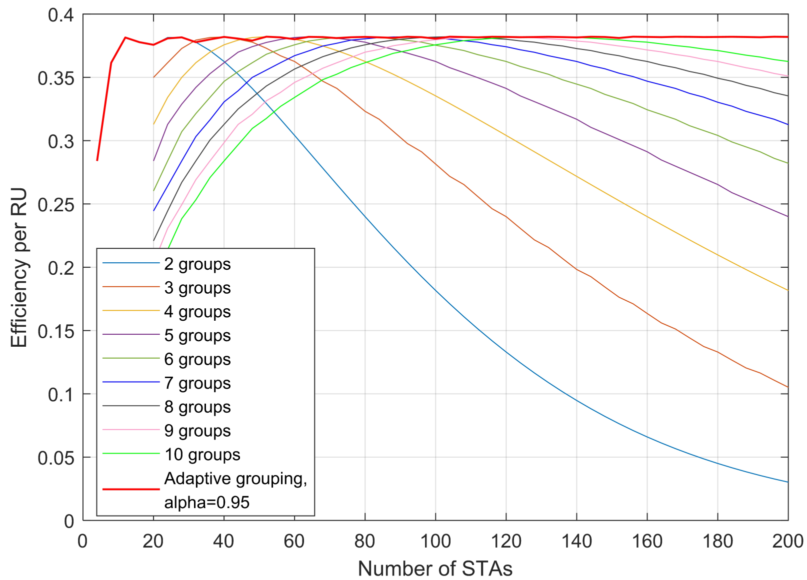

Figure 3.6: RU efficiency of proposed Adaptive grouping scheme vs certain number of groups strategy.

3.6.3 Throughput Performance

To evaluate the throughput of both system and single STA, the expression of throughput is derived in this subsection. The time duration of successful transmission is given by:

$$T_{duration} = T_{DIFS} + T_{trigger} + 2 * T_{SIFS} + T_{PPDU} + T_{MBA}. \tag{3.18}$$

When the transmission in all RUs are failed, the time duration is calculated as:

$$T_{idle} = T_{DIFS} + T_{trigger}. \tag{3.19}$$

The estimation of time duration of one group is given as:

$$E[T] = T_{idle}P_{idle} + T_{duration}P_{succ}. \tag{3.20}$$

The throughput of the system equals to:

$$Th_{sys} = \frac{r * \eta * D_{payload}}{E[T]}, \tag{3.21}$$

Table 3.2: Simulation parameters in Chapter 3

Parameter	Value	Parameter	Value
r	9	T_{DIFS}	$34\mu s$
m_0	2	T_{PIFS}	$25\mu s$
W_0	7	$T_{trigger}$	$112\mu s$
α	0.95	T_{SIFS}	$16\mu s$
Payload	1000bits	T_{MBA}	$150\mu s$
MCS	9	T_{BSR}	$80\mu s$
GI	$0.8\mu s$		

where $D_{payload}$ is the payload. The average throughput of single user in the system is formulated as:

$$Th_{SU} = \frac{\tau * (1-p) * D_{payload}}{E[T]}. \tag{3.22}$$

The simulation parameters are assumed in Table 3.2, according to the draft standard of IEEE 802.11ax.

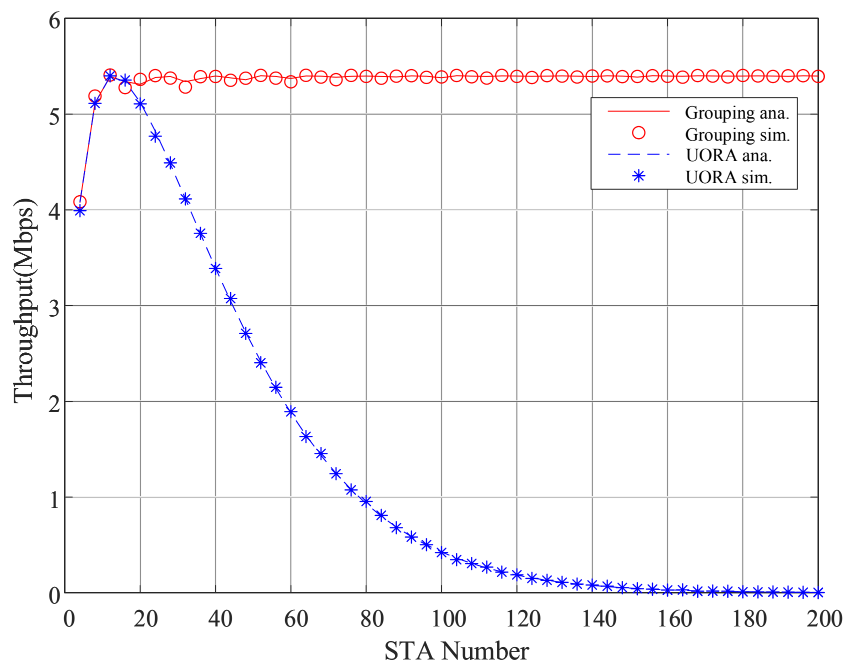

Figure 3.7: System throughput of adaptive UORA grouping scheme compared with conventional UORA.

The numerical result of system throughput is shown in Figure 3.7, compared with the

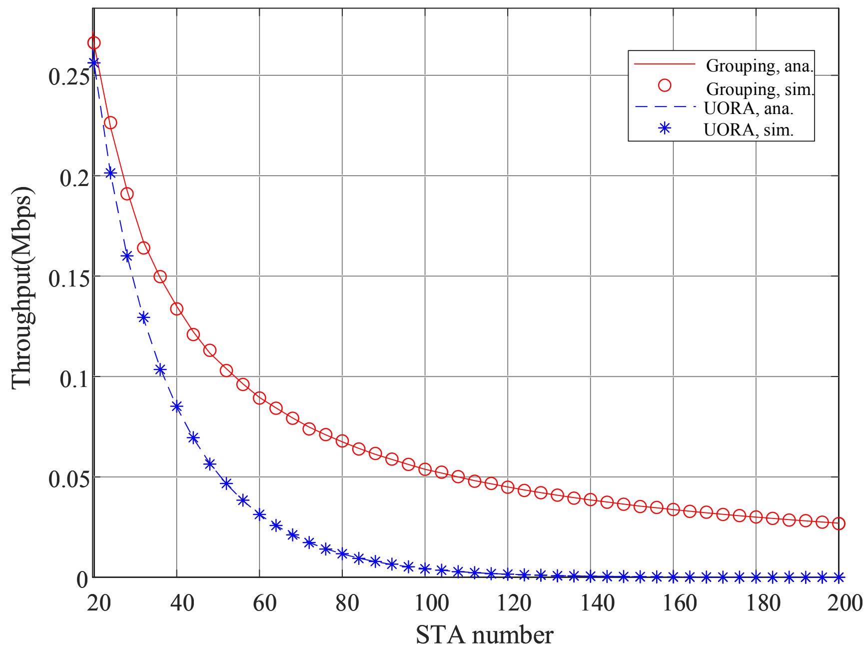

Figure 3.8: Single user throughput of adaptive UORA grouping scheme compared with conventional UORA.

conventional UORA process. Meanwhile, the average throughput of single STA is presented in Figure 3.8. As is shown in Figure 3.7 and Figure 3.8, the grouping algorithm is not working until the system throughput falls from the summit. With increasing number of STAs, the performance of conventional UORA degrades sharply because of the rising collision probability. However, the proposed grouping algorithm maintains the near-summit performance by controlling the group sizes. These two figures show the significant throughput improvement of the proposed grouping algorithm in the ultra-dense networks. For instance, the grouping algorithm provides 1051 times gain when $n = 200$.

3.7 Summary of the Chapter

This chapter proposed an adaptive grouping scheme to address the high collision of UORA in the ultra-dense 802.11ax network. The system model of proposed UORA grouping scheme was formulated, the relationship between STAs number with RU efficiency was studied, and optimal group size was derived. Meanwhile, because there are usually remainders after grouping, which degrades the performance of the whole system, we also derived an adaptive range of group size and proposed an adaptive grouping algorithm. The numerical results showed that proposed adaptive grouping maintained the performance of UORA and was superior to the conventional UORA. A new adaptive grouping algorithm is proposed in Section 3.5 based on the results of adaptive group size, which ease the performance fluctuation after grouping; The performance of proposed algorithm is evaluated by numerical results in Section 3.6;

Chapter 4

BSR based Two-stage Mechanism (BTM) and BTM Grouping Scheme

4.1 Overview

The UORA in 802.11ax is an essential multi-user (MU) access mechanism, multiple S-TAs can directly access the AP simultaneously without the assistance of other additional information. One critical problem of UORA is the rising collision rate caused by increasing STAs number. Because the access contention happens in RUs, where STAs transmit their data package-PPDU (Presentation Protocol Data Unit), the channel utility efficiency degrades when the collision rate is high. Therefore, limit the access number of STAs can effectively maintain the channel utility efficiency in the network, such as the grouping scheme proposed in the previews chapter, which limits the access STA number is a time period. However, the optimal efficiency after grouping is still low because of the ALOHA design in the UORA, as is shown in Fig. 4.1.

In Fig. 4.1, even though the proposed UORA grouping scheme maintains the optimal efficiency, it is still lower than 40 percent. According to (3.10), the optimal RU efficiency of UORA is equal to $(1 - \frac{1}{N})^{N-1}$, which is degrading when as STA number rise and approach to $1/e \approx 37\%$. This means that if the UORA mechanism is directly used for data transmission, the wasted channel resource will be higher than 60 percent. In order to cope with this drawback as well as retain the advantages of UORA, the BSR based Two-stage Mechanism (BTM) is

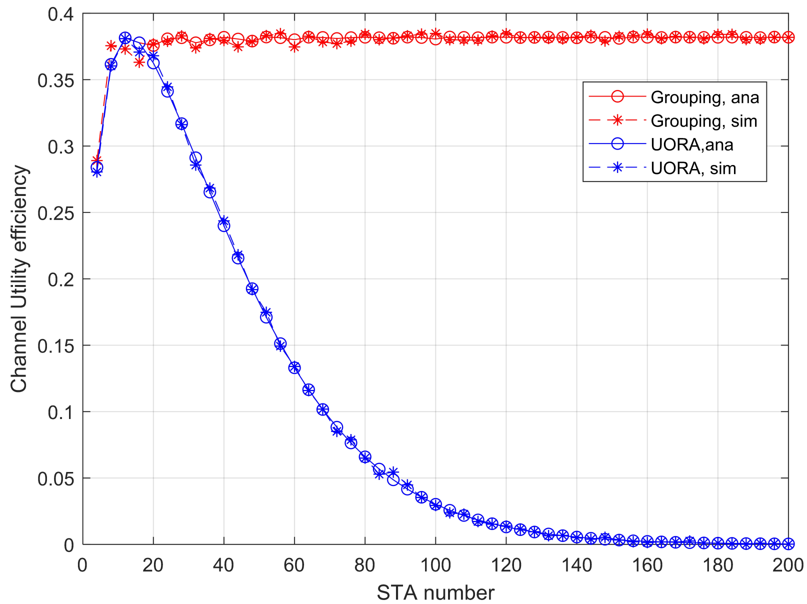

Figure 4.1: Low efficiency of UORA even after grouping.

proposed.

In this chapter, we adopt and study the grouping scheme in BTM. The rest of this chapter is organized as follows: Section 4.2 introduces the process details of the BSR based Two-stage. Section 4.3 formulates and analysis the BTM grouping scheme. Section 4.4 evaluates the performance of the proposed scheme by simulation results. This chapter is summarized in Section 4.5.

4.2 BSR based BSR based Two-stage Mechanism (BTM)

BSR based Two-stage Mechanism (BTM) is a UL MU transmission process for IEEE 802.11ax. By separating the access process with resource allocation , BTM maintains the advantage of UORA, which allows STAs directly access the AP without pre-scheduling information, and provides AP the flexibility to control the resource allocation for accessed STAs.

In the first stage, which is a UORA based mechanism for BSR transmission. As is introduced in the Chapter 2, BSR contains the information of STAs' buffers, which facilitates AP to schedule the following resource allocation. In the second stage, AP allocates RUs to accessed STAs in the first stage based on the BSRs. The directly allocation of RU avoid the possible collisions in data transmission stage. The details of BTM is illustrated are follows:

The AP sent a BSRP-TF to initiate and synchronize the BSR mechanism, then STAs, who received the BSRP-TF and prepared to UL transmission, will report the data frame size and QoS level of their following transmission in their BSR frames. The access of BSR frames following the same rule as convention UORA mechanism. After AP received the BSR frames sent by STAs, it will feedback a Multi-BlockAck (M-BA) frame and mentioned the STAs who successfully transmitted their BSR frames. After the execution of the BSR mechanism, AP can schedule the RU allocation according to the data frame size and QoS level of different STAs. AP firstly broadcast a regular trigger frame, which contains the information of RU allocation. STAs transmit their data frames according to this allocation, then AP feedback another M-BA frame after it received these data frame. This data transmission process is scheduled by AP based on previews information in BSR, so it is a contention-free process without wasting channel resource.

The whole process introduced above including two stages: 1. BSR mechanism is adopted to solicit the necessary information for scheduling, called **information soliciting stage**; 2. Conventional trigger-based transmission is adopted for data transmission, called **data transmission stage**.

Because the information soliciting stage adopts the UORA mechanism, which does not require the information for scheduling but suffers from low efficiency. However, BTM adopts an addition collision-free transmission stage to improve the utility of channel resources. In the saturated networks, all STAs will capture as much RUs as possible, even though in information soliciting stage there are collisions happen, once there is at least one STA accessed AP by its BSR, all RUs can be allocated and there is no waste of channel resources. The separation of the access process and data transmission process effectively improves the throughput of accessed STAs and the whole system. However, the collision in the information soliciting stage still degrades the access number of STAs, when the STA number is very high, the collision is still critical enough that even one STA cannot access the AP. Therefore, in order to improve the performance of this two-stage mechanism, we proposed a grouping scheme to optimize the access efficiency in information soliciting stage, which also improves the performance of each STA and the whole system as well in the ultra-dense scenario. The whole process of BTM is illustrated in Figure 4.2.

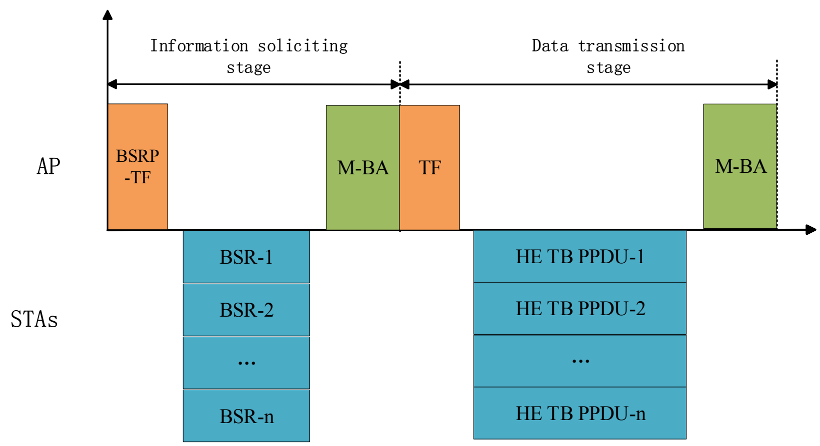

Figure 4.2: The process illustration of BTM.

The access performance of BSR frames directly influence the efficiency of information soliciting, so the concept BSR delivery rate is used to evaluate the access efficiency of the BSR frames [31].

Suppose in one STA, all transmission information, such as size and QoS of the pending data frame, can be delivered to AP by one BSR frame. Generally, each STA only need to access one BSR-RU each time, either the STA or the network will not gain benefit if the STA access extra BSR-RUs. With this assumption, the access number of BSR frames is equal to the number of accessed STAs.

The separation of the access process and data transmission process effectively improves the throughput of the whole system. However, the collision in the information soliciting stage (by UORA) is still critical. It degrades the access number of STAs when the STA number is very high. Therefore, we propose an adaptive BTM grouping scheme in this thesis, which is illustrated in Section 4.3.

4.3 Analysis Model of BTM Groping Scheme

The BTM grouping scheme is a TWT based grouping scheme for UL MU transmission. The time domain is divided into several service period, only one group of STAs can access AP in each service period. In the service period, the group of STA access AP by BTM and turn into doze state when this service period finishes until the next service period. The BTM grouping scheme is illustrated in Figure 4.3.

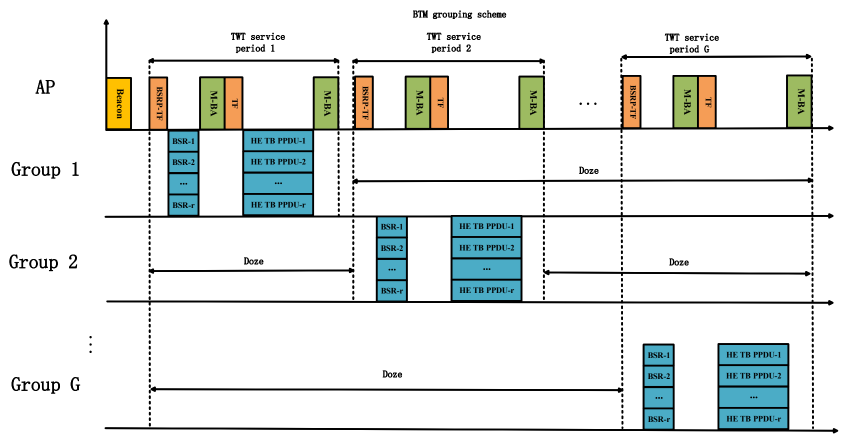

Figure 4.3: The process illustration of BTM grouping mechanism.

There are two major parts in proposed BTM grouping scheme: 1. Grouping part; 2. Transmission part. In the grouping part, the AP firstly calculates the optimal group size and group and virtually divides all STAs into several groups. Then AP adopts TWT mechanism to implement the grouping strategy. In the TWT mechanism, AP broadcast a beacon frame to initial the mechanism and schedules the transmission time of different groups. Each group has its individual transmission time duration, called service period. The STA in one group only wake up in their own service period and turn into doze state after transmission until the next service period. The transmission part happens in the service period, where the BTM is adopted as the transmission method. STA follows the process of BTM, information soliciting stage and data transmission stage, to complete the data transmission.

This section will formulate the system model of BTM grouping scheme. Considering the two stages transmission of BTM, the formulation of these two stages are separated.

The first stage is the information soliciting stage, because AP has no information about S-TAs buffer status, therefore the conventional UORA is adopted to solicit the BSR frames from STAs. Meanwhile, in order to ease the high collision rate, the grouping scheme is adopted. According to Chapter 3, in order to maintain the optimal RU efficiency, the optimal group size should be calculated according to (3.4) and (3.9). In order to further ease the performance fluctuation caused by remainder after grouping, the variable group size is proposed and calculated in (3.11). The grouping scheme is proposed in Algorithm 1. With UORA grouping scheme, the optimal group size can be calculated by (3.10), and the STA number in each group N_j is derived by Algorithm 1. The RU efficiency of each group can be calculated by (3.16):

$$\eta_j(p) = N_j(1-(1-p_j)^{\frac{1}{N_j-1}})(1-p_j),\ j \in [1, G],$$

which can be regarded as the probability that one RU successfully access one STA' s BSR request. After the contention process for the first stage, the AP will allocate RU to STAs who successfully transfer their BSR to AP.

In this section, we will focus on formulate the model of the second stage. Assume that all users are the same and the saturated, in this case, the AP averagely divides the all r RUs to all accessed users. For each 20MHz channel, there are $r = 9$ RUs, which can support maximal 9 STAs simultaneously. Suppose the number of accessed STAs is NA_j, where j is the $j-th$ groups. The new notations involved in this section is presented in Table 4.1.

Table 4.1: Notations definition

Notations	**Meaning**
NA_j	Number of accessed STAs in the j-th group
$RU_{i,j}$	Number of allocated RU for the i-th STAs in the j-th group
Th	Average system throughput
Th_j	Average system throughput when service the the j-th group
Th_{STA}	Average throughput of each STA
$Th_{STA,j}$	Average throughput of each STA in the the j-th group

According to (3.16), the number of accessed STAs NA_j is expressed as:

$$NA_j = N_j * \eta_j(p), j \in [1, G]. \tag{4.1}$$

Therefore, for each transmission with NA_j access STAs, each accessed STA is allocated with $RU_{i,j}$ RUs, which can be calculated by:

$$RU_{i,j} = \left\lfloor \frac{r}{NA_j} \right\rfloor, i \in [1, NA_j], j \in [1, G]. \tag{4.2}$$

Generally, there are (r mod NA_j) RU left as remainder after dividing shown in (4.2). In this case, AP randomly allocates them into (r mod NA_j) of STAs, each STA should has one more RU. Therefore the RU allocation can be written as:

$$RU_{i,j} = \begin{cases} \left\lfloor \frac{r}{NA_j} \right\rfloor + 1, & i \in [1, r \bmod NA_j], j \in [1, G]; \\ \left\lfloor \frac{r}{NA_j} \right\rfloor, & i \in [(r \bmod NA_j) + 1, NA_j], j \in [1, G]. \end{cases} \tag{4.3}$$

Because there is $r = 9$ RUs in each group, in the saturated scenario, if there is at least one STA successfully transmits BSR to AP, all RUs can be allocated for data transmission. Therefore the average RUs for each STA in each group can be expressed as:

$$E\left[RU_j\right] = \frac{\sum_{i=1}^{NA_j} RU_{i,j}}{N_j} = \frac{r}{N_j} \tag{4.4}$$

Furthermore, the throughput of BTM grouping mechanism in each group should be equal to the data transmission capacity of this grouping, unless there is no STA successfully access the AP. The throughput in each group is written as:

$$Th_j = \frac{r * (1 - (1 - eff)^r) * L_{payload}}{E\left[T\right]}, \tag{4.5}$$

where $L_{payload}$ is the length of payload and $E\left[T\right]$ is the expectation time duration in each group. With the given throughput of each grouping, the average system throughput can be expressed as:

$$Th = \frac{1}{G} \sum_{j=1}^{G} Th_j. \tag{4.6}$$

And the average throughput of each STA is written as:

$$Th_{STA} = \frac{\tau * (1 - p) * E[RU_j] * L_{payload}}{E[T]}. \tag{4.7}$$

Theoretically, the average system throughput of proposed BTM grouping scheme should be better than the conventional UORA grouping, because of the higher RU efficiency. To illustrate this statement, the numerical results is presented in the next section.

4.4 Numercial Results of BTM Grouping Scheme

In this section, the performance of proposed BTM grouping scheme is evaluated by numerical results. The performance of proposed BTM grouping scheme should superior to the UORA grouping according to the analysis of section 4.3, while this statement should also be evaluated by the simulation. The simulation parameters are given in Table 4.2

Table 4.2: Simulation Parameters in Chapter 4

Parameters	**value**	**Parameters**	**value**
r	9	W_0	7
m_0	2	Payload	1000 bytes
Trigger	89 bytes	BSR	32 bytes
M-BA	46 bytes	SIFS	16 μs
DIFS	34 μs	MCS	9
GI	0.8 μs	Rate	11.8Mbps

Without specific statement, all simulation parameter of this Chapter is shown in the Table 4.2. We still consider a networks with N STAs and one AP, the channel bandwidth is 20MHz. In order to present the performance of proposed BTM grouping scheme, both simulation and analysis results compared among proposed BTM grouping, UORA grouping, conventional BTM and conventional UORA. The performances are shown in Fig. 4.4:

The throughput of BTM is higher than UORA either in grouping scheme or non-grouping scheme, also the grouping scheme is superior to the non-grouping scheme either in BTM or UORA, as is presented in the Figure 4.4. This simulation results (points in the Figure 4.4) closely attach to the analysis results (lines in the Figure 4.4). The proposed BTM grouping scheme overwhelms to other schemes in the system throughput, especially when STA number is high. Because the proposed BTM grouping scheme ease the collision by dividing STAs into groups along the time domain and BTM mechanism utilizes all channel resources as well. Furthermore, the performances of average throughput of each STA are also presented with different access mechanism, which are shown in Figure 4.5, 4.6.

The propose BTM grouping scheme has an advantage over other schemes in both system and each STA throughput, especially in the ultra-dense network. Meanwhile, there is almost

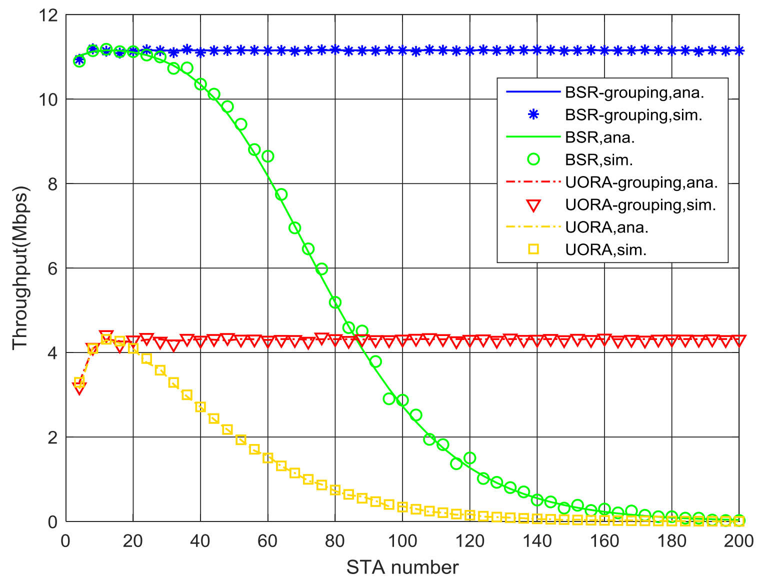

Figure 4.4: System Throughput of BTM grouping compared with convention UORA, conventional BTM and proposed UORA grouping in Chapter 3.

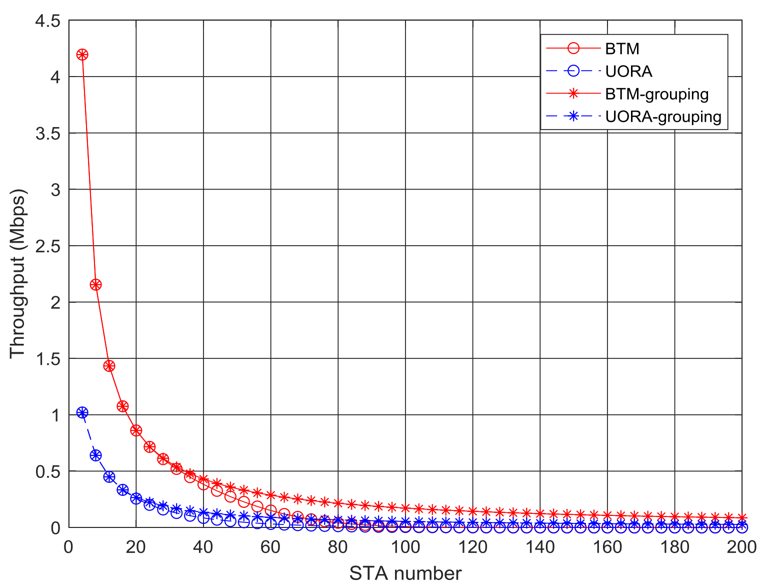

Figure 4.5: BTM grouping throughput of each STA with convention UORA, conventional BTM and proposed UORA grouping in Chapter 3.

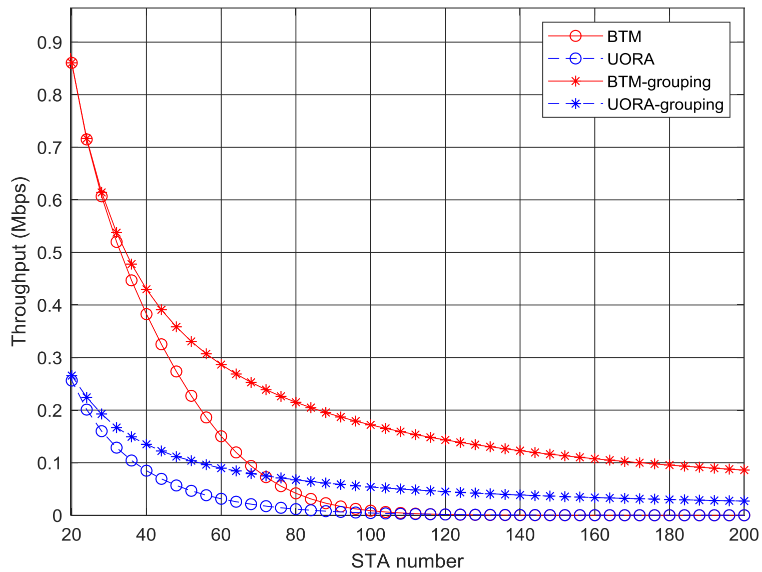

Figure 4.6: BTM grouping throughput of each STA with convention UORA, conventional BTM and proposed UORA grouping in Chapter 3 (zoom in).

no throughput for each STA in the non-grouping scheme because of the very high collision rate in the ultra-dense scenario. Therefore, the proposed BTM grouping scheme further enhance the performance of proposed UORA grouping scheme.

4.5 Summary of the Chapter

In this chapter, the grouping scheme proposed in Chapter 3 is adopted and studied in BTM to further improve the performance of both system and each STA. The process details of the BTM is illustrated, formulated and analyzed. Finally, the numerical results are presented to e-valuate the performance of proposed scheme. The BTM shows better system performance than conventional UORA, and the proposed BTM grouping scheme has overwhelming throughput performance than other schemes.

Chapter 5

Hybrid BTM Grouping Scheme and Utility Enhancement

5.1 Overview

Generally, in the realistic MU UL process of 802.11ax network, with the ultra-dense and diverse STAs, the service requirements are also diverse. In order to satisfy these requirements, we propose the hybrid BTM grouping scheme. The major changes are illustrated as follows.

In information soliciting stage, both random access and the scheduled scheme will be adopted. If the transmission timing of user is predictable with acceptable accuracy, scheduling the access of users will be more efficient than random access. While if AP has no idea when which user will transmit, the aimless scheduling will only degrade the system performance. Therefore, in the information soliciting stage, both these two methods will be adopted to maintain the BSR delivery rate of the network.

In the transmission stage. The major problem is the allocation scheme of the RUs. This scheme should content the demands of users as well as the network RU efficiency. Therefore, the rest RUs will be allocated for UORA after scheduling. Meanwhile, users usually have multi-dimension QoS demands, these demands have different kinds of requirements of the allocation scheme. For instance, the user which has low-latency requirement will be allowed to access more frequently between different groups, but they may only need one or two RUs in each time period; the user which has high data rate requirement will be assigned more RUs in one period of time, while it is not necessary to assign them in sequence.

After each transmission, the quality of service is evaluated by latency. For each service on the STA, it can value the service quality by the linear function, call **QoS utility function**. This function is used to value the QoS performance of proposed hybrid BTM grouping scheme.

The proposed Hybrid BTM grouping scheme allows scheduled STAs access multiple times in one big grouping period by multiply cross-group access, which provides lower latency experience for scheduled STAs. Meanwhile, the STAs are divided into two types according to their sensitivity about latency. The proposed grouping algorithm will assign the latency sensitive STAs as scheduled STAs for better QoS performance.

The rest of this chapter is organized as follows: Section 5.2 presents the formulation process and proposed algorithm; Section 5.3 shows the numerical results of proposed algorithm, with different dimensions of performances and considering diverse factors that influence these performances. This chapter is summarized in Section 5.4.

5.2 System Model of Hybrid BTM Grouping & Proposed Algorithm

In the proposed access mechanism, the AP uses the hybrid strategy. In the scheduled part, STAs are multiply allocated across groups in one big grouping period. Suppose there are N_s STAs need to be scheduled, the k-th STA has the given repeat requirement $Rpa_k(k \in [1, N_s])$, which is given by the AP according to the requirement of the service in scheduled STA (we suppose it is a constant in this thesis). because the RUs are regarded as the same to STAs, all scheduled STAs are averagely allocated in each group and the rest RUs are assigned for random access. In the random-access part, STAs access AP by the rest of RUs after scheduled. AP divides UORA STAs into groups to ease the collision and calculates the optimal group number and group sizes. In the system model of this paper, STAs are separated into two parts, scheduled STAs (N_s) and UORA STAs (N_{RA}), the sum of these two parts' STAs are:

$$N_{RA} + N_s = N, \tag{5.1}$$

where N is the total number of STAs in the network. In each group, AP assign r_s RUs to the scheduled STAs and r_{uo} RUs to the UORA STAs:

$$r_s + r_{RA} = r, \tag{5.2}$$

where r is the RUs number in each group. In the hybrid access, the performance of scheduled access is determined. In order to study the influence of the hybrid access, it is necessary to study how number of RU r_{uo} influence the performance of UORA in grouping. The performance of conventional UORA is given by [40]:

$$\tau = \frac{W_0 + 1}{W_0 + 1 + (1 - p) X_0 + (1 - p) \sum_{i=1}^{m-1} X_i \left(\frac{p}{2}\right)^i + X_m \left(\frac{p}{2}\right)^m}, \tag{5.3}$$

where

$$X_i = (-\frac{r}{2}\left\lfloor \frac{W_i}{r} \right\rfloor^2 + (W_i - \frac{r}{2})\left\lfloor \frac{W_i}{r} \right\rfloor),$$

and

$$W_i = 2^i(W_0 + 1) - 1, i \in [1, m - 1].$$

The probability p that collision happens in one RU can be derived as:

$$p = 1 - \left(1 - \frac{\tau}{r}\right)^{n-1}. \tag{5.4}$$

And the efficiency of each RU is written as:

$$eff = \frac{n\tau (1 - p)}{r}. \tag{5.5}$$

According to Proposition 1, the efficiency is maximized when:

$$n (1 - p)^{\frac{1}{(n-1)}} - n + 1 = 0, n \in [2, \infty), p \in [0, 1]. \tag{5.6}$$

The optimal number of STAs in each group can be calculated by:

$$\frac{W_0+1}{W_0+1+\left(1-\frac{1}{n}\right)^{n-1}\sum_{i=0}^{m-1}X_i\left(\frac{1-\left(1-\frac{1}{n}\right)^{n-1}}{2}\right)^i+X_m\left(\frac{1-\left(1-\frac{1}{n}\right)^{n-1}}{2}\right)^m}-\frac{r}{n}=0, n\in[2,\infty)\,. \tag{5.7}$$

According to (5.7), for any given r_{uo}, the correspond optimal group size N_{opt} can be calculated, and the group number G can be calculated by:

$$G=\left\lfloor\frac{N_{uo}}{N_{opt}}\right\rfloor. \tag{5.8}$$

The number of scheduled STA N_s is determined by AP, which will judge the QoS preference of each STAs to improve the QoS utility of each STA. The details QoS utility will be illustrated in section 5.3.

Becasue the N_s, $f=\frac{Rpa_k}{G}$ can be calculated by the AP, where f is the average access frequency for cross-group multi-allocation when grouping. Suppose in one big grouping period, there are R_s are scheduled, which can be expressed as:

$$R_s=\sum_{k=1}^{N_s}Rpa_k=\sum_{j=1}^{G}r_{s,j}. \tag{5.9}$$

The number of scheduled RU in each group $r_{s,j}$ is impacted by the number of the group number G. That means the number of UORA RU also impacted by G. For simplification, we suppose that all scheduled RU R_s are averagely allocated in each group. If there are remainders left after dividing, there will be allocated from the first group. Rewrite (5.9), the estimation of r_s in each group can be calculated by:

$$\widehat{r_s}=\frac{R_s}{G}=\frac{\sum_{k=1}^{N_s}Rpa_k}{G}=\sum_{k=1}^{N_s}f_k, \tag{5.10}$$

where the f_k is the access frequency requirement of the k-th scheduled STAs, which is directly related to the latency requirement. In this thesis we regard it as given constant. Since the cross group multiple allocation is designed for low latency transmission, while the group number vary when network scenario is changing, therefore AP will use the access frequency $f_k=\frac{Rpa_k}{G}$, $f\in[0,1]$ to adjust the average latency of STAs. Rpa_k is the access times in one big grouping period.

With the given f_k of each scheduled STA and number of scheduled STAs N_s, the estimated number of assigned RU $\widehat{r_s}$ can be calculated. Therefore, the estimated number of RU for random access $\widehat{r_{uo}}$ can also be calculated.

Rewrite (5.2), (5.7), (5.8), the estimation of optimal group size for random access $\widehat{N_{opt}}$ can be calculated by:

$$\frac{\widehat{N_{opt}}\,(W_0+1)}{W_0+1+\left(1-\frac{1}{\widehat{N_{opt}}}\right)^{\widehat{N_{opt}}-1}\sum_{i=0}^{m-1}X_i\left(\frac{1-\left(1-\frac{1}{\widehat{N_{opt}}}\right)^{\widehat{N_{opt}}-1}}{2}\right)^i+X_m\left(\frac{1-\left(1-\frac{1}{\widehat{N_{opt}}}\right)^{\widehat{N_{opt}}-1}}{2}\right)^m}-\left(r-\sum_{k=1}^{N_s}f_k\right)=0. \tag{5.11}$$

The group number G can be calculated by:

$$\left\lfloor\frac{N_{uo}}{\widehat{N_{opt}}}\right\rfloor=G, \tag{5.12}$$

and the total number of assigned RU in one big grouping period R_s is derived as:

$$R_s=\left\lceil G*\sum_{k=1}^{N_s}f_k\right\rceil. \tag{5.13}$$

The group number G and the total RUs for scheduled STA R_s can are given. Therefore, the average RUs in each group can be calculated by:

$$r_s=\frac{R_s}{G}. \tag{5.14}$$

According to the value of r_s, there are three possible scenarios after allocated the scheduled STAs: Scheduled STAs are equal in each group (r_s is integer, $r_s\in(0,r)$); Scheduled STAs in some groups is more than others because of remainder after dividing (r_s is not an integer, $r_s\in(0,r)$); Scheduled STAs occupy all RUs ($r_s=r$). Three examples are shown in Figure 5.1-5.3 for better illustration.

With the given G, $\widehat{N_{opt}}$ and $\widehat{r_s}$ by (5.11),(5.12), and (5.14), the group dividing of N_{RA} can be completed according to different scenarios, which is expressed in the Algorithm 2.

Generally, there are three parts in Hybrid grouping algorithm for different allocation s-

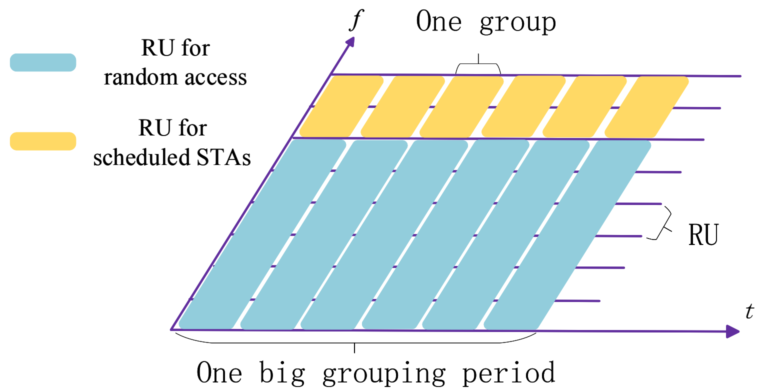

Figure 5.1: Hybrid grouping scheme where scheduled STAs are equal in each group.

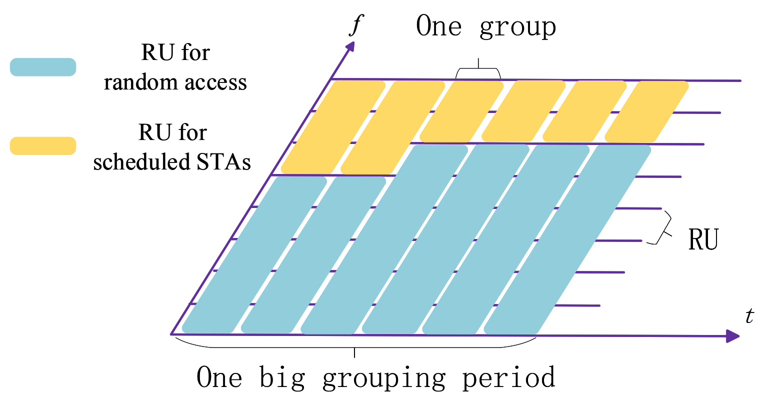

Figure 5.2: Hybrid grouping scheme where remainders left after dividing scheduled STAs in each group.

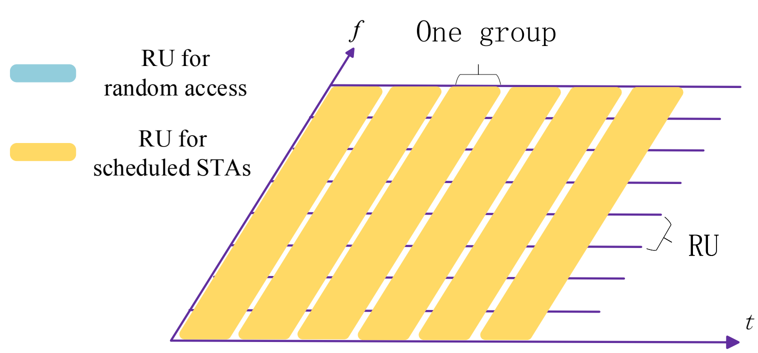

Figure 5.3: Hybrid grouping scheme where scheduled STAs occupy all RUs.

cenarios. If the number of scheduled RUs is larger than the total available RUs, all RUs will be allocated for scheduled transmission. If the number of scheduled RUs can be divided by number of groups without remainder, these RUs can be averagely allocated to each group, then using Algorithm 1 to schedule the STAs for random access. If number of scheduled RUs cannot be divided by number of groups without remainder, the Algorithm 3 will be run to schedule the allocation and grouping scheme.

After dividing STAs into groups, Suppose each group has $N_{RA,j}$ SATs, which following constrain:

$$N_{RA} = \sum_{j=1}^{G} N_{RA,j} \tag{5.15}$$

Algorithm 2: Hybrid grouping algorithm

Input: G, $\widehat{N_{opt}}$, r, N_{RA}, N_s, $\widehat{r_s}$.
Output: $r_{s,j}$, $N_{RA,j}$, where $\forall j \in [1, G]$

if $\widehat{r_s} \geq r$ **then**
  $G <= 1$
  $r_{s,1} <= r$
  $N_{RA,1} <= 0$
else if $\widehat{r_s} == \widehat{r_s} - \lfloor \widehat{r_s} \rfloor$ **then**
  if $N_{RA} \leq \widehat{N_{opt}}$ **then**
    $G <= 1$
    $N_{RA,1} <= N_{RA}$
    $r_{s,1} <= \lfloor \widehat{r_s} \rfloor$
  else
    Fun Algorithm 1 to schedule STA for random access.
  for $j \in [1, G]$ **do**
    $r_{s,j} <= \lfloor \widehat{r_s} \rfloor$
    $r_{RA,j} <= r - r_{s,j}$
else if $0 < \widehat{r_s} < r$ **then**
  Run Algorithm 3 to schedule STA for both random and scheduled access.

Suppose in j_{th} group, there are $r_{s,j} = r - r_{uo,j}$ scheduled users. Then the total group number of j-th group is $N'_j = N_j + r_{s,j}$. For different r_{uo}, the optimal efficiency η_{opt} are different, therefore the allocation should maximize the average $\eta = \sum_{j=1}^{G} r_{RA,j} * \eta_j$.

The main purpose of the proposed hybrid grouping algorithm is to improve the system performance under a system model that is more close to realistic transmission scenario. The

Algorithm 3: Hybrid grouping algorithm for fraction allocation r_s

Input: G, $\widehat{N_{opt}}$, r, N_{RA}, N_s, $\widehat{r_s}$.
Output: $r_{s,j}$, $N_{RA,j}$, where $\forall j \in [1, G]$

$R_s <= \lfloor G * \widehat{r_s} \rfloor$
$mod1 <= mod(R_s, G)$
$mod2 <= mod(N_{RA}, G)$
$mod3 <= mod(mod2, G - mod1)$
if $G = 1$ **then**
    $N_{RA,1} <= N_{RA}$
    $r_{s,j} <= \lfloor \widehat{r_s} \rfloor$
    $r_{RA,j} <= r - r_{s,j}$
else if $mod3 = 0$ **then**
    for $j \in [1, G]$ **do**
        if $j \in [1, mod1]$ **then**
            $N_{RA,j} <= \left\lfloor \frac{N_{RA}}{G} \right\rfloor$
            $r_{s,j} <= \lfloor \widehat{r_s} \rfloor + 1$
        else
            $N_{RA,j} <= \left\lfloor \frac{N_{RA}}{G} \right\rfloor + \left\lfloor \frac{mod2}{G - mod1} \right\rfloor$
            $r_{s,j} <= \lfloor \widehat{r_s} \rfloor$
else
    for $j \in [1, G]$ **do**
        if $j \in [1, mod1]$ **then**
            $N_{RA,j} <= \left\lfloor \frac{N_{RA}}{G} \right\rfloor$
            $r_{s,j} <= \lfloor \widehat{r_s} \rfloor + 1$
        else if $j \in [mod1 + 1, mod1 + mod3]$ **then**
            $N_{RA,j} <= \left\lfloor \frac{N_{RA}}{G} \right\rfloor + \left\lfloor \frac{mod2}{G - mod1} \right\rfloor + 1$
            $r_{s,j} <= \lfloor \widehat{r_s} \rfloor$
        else
            $N_{RA,j} <= \left\lfloor \frac{N_{RA}}{G} \right\rfloor + \left\lfloor \frac{mod2}{G - mod1} \right\rfloor$
            $r_{s,j} <= \lfloor \widehat{r_s} \rfloor$

major index to value the performance including the latency, BSR delivery rate as well as QoS Utility. AP will choose the high priority STAs as scheduled STAs to optimal the QoS Utility. Throughput is not involved as the major index because BTM has guaranteed the throughput to maximum, it will only be influenced by the length of data frame in our model.

The concepts of BSR delivery rate and QoS Utility will be illustrated in Section 5.3. There are several factors that influence the performance of proposed hybrid grouping algorithm. In the following section, we will consider these factor one by one to evaluate the performance of proposed algorithm in Section 5.3.

5.3 The Numerical Results of Proposed Hybrid BTM Grouping Algorithm

This section will evaluate the performance of proposed Hybrid Grouping Algorithm through the numerical results. In the simulation, several dimensions of variants are considered, including the number of scheduled STA (fixed number or proportion of total number), different access frequency of scheduled STA and the length of the data package. The default values of simulation parameters are shown in Table 5.1.

Table 5.1: Simulation Parameters in Chapter 5

Parameters	**value**	**Parameters**	**value**
N_s	$0.1N$	f	0.9
w_1	1	w_2	0.1
r	9	W_0	7
m_0	2	Payload	1000 bites
Trigger	89 bytes	BSR	32 bytes
M-BA	46 bytes	SIFS	16 μs
DIFS	34 μs	MCS	9
GI	0.8 μs	Rate	11.8Mbps

The default simulation parameter in this section is presented in Table 5.1 unless there is specific statement. In this section, we will use several factors to evaluate the performance of proposed hybrid grouping algorithm, including average BSR delivery rate in the network, the average latency per STA and the average utility of latency per STA.

The concept of BSR delivery rate in 802.11ax is firstly proposed in [45]. This factor reflects the BSR delivery efficiency of the network. Comparing the influence of system throughput, BSR delivery rate reflects the capability of effective UL MU access. Total BSR delivery rate can by express by sum of scheduled and random access BSR rate, which can be express as [45]:

$$BSR_j = r_{s,j} + N_{uo,j}\tau_j\left(1 - p_j\right) \tag{5.16}$$

The parameters τ and p represent the probability that STA go through the backoff stage and the collision rate when access the RU, they can be calculated according to (5.3), (5.4), respectively. The probability that one STA successfully access can also be expressed by these two parameters:

$$P_s = \tau(1 - p) \tag{5.17}$$

With the probability of successfully access, the average latency of random access STAs is expressed as:

$$T_{latency} = \frac{T_{duation} * G}{P_s} \tag{5.18}$$

In this thesis, we use the performance of latency as an example of QoS property. Considering the diversity of IoT devices in the ultra-dense network, the preference of QoS is different from device to device. In order to evaluate the expression and value the different preference of QoS performance, the concept of QoS utility is proposed and the utility function is expressed as follows:

$$U_i = \frac{w_i}{T_{latency_i}} \tag{5.19}$$

where the w_i is the weigh that this STA value the latency. The weighted mean method is widely adopted to evaluate the different preference of resources [28], [29]. Generally, there are several dimension factors to evaluate the utility. In this thesis, we focus on latency and suppose there are only two types of STAs, latency sensitive and latency non-sensitive, for simplification. The latency sensitive STA will value the latency performance much higher than the latency non-sensitive STA, which means their w_i is higher. We suppose the w_1 represents the wight for latency sensitive STAs and w_2 represents the wight for latency non-sensitive STAs. Therefore, the sum of utility function of all STA is written as:

$$U = \sum_{i=1}^{N} U_i, \tag{5.20}$$

and the average utility of each STA can be expressed as:

$$E[U_i] = \frac{U}{N}. \tag{5.21}$$

As mentioned in Section 5.2, there are many factors that influence the performance of proposed algorithm. In our system model, we consider the coexisting of both scheduled and random access STAs in the network. In the realistic transmission scenario, the number of scheduled STA may be fixed or dynamic. We considered the fixed number of scheduled STA in Section 5.3.1 and proportional scheduled STA number of total STA in Section 5.3.2 for simplification, and we compare these two different scenarios in Section 5.3.3. Meanwhile, due to the diversity of services on the STAs, the requirement of access frequency for scheduled STAs are also different. In Section 5.3.4, the presented numerical results show how the different access frequency requirement influence the performance of system and each STAs. Finally, the length of data frame packet is also considered, in Section 5.3.5, the performance, such as system throughput, average latency per STA and the QoS utility, are presented with big and small size of data frame.

Note that the "latency" and "utility" presented in figures mean the average performance on each STA in the following subsection.

5.3.1 Fix Number of Scheduled STAs

This subsection considered the fixed number of scheduled STAs in the hybrid transmission scenario, other factors are set with default value shown in Table 5.1. Generally, this scenario can be equalized as the UORA grouping model with smaller number of available RUs. The BSR delivery rate of this scenario is shown in Figure 5.4. The proposed grouping method

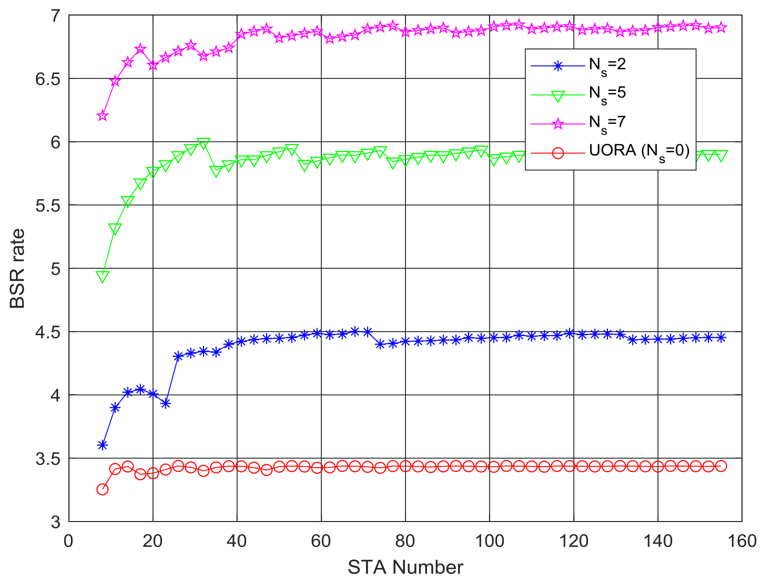

Figure 5.4: BSR delivery rate of hybrid scheme with fixed number of scheduled STAs.

maintains the BSR rate performance even when the number of STA is very high (200). The B-SR delivery rate is improving as the number of scheduled STA is rising. Because the efficiency of UORA is around 37 percent, the scheduled access is more efficiency. Therefore with more scheduled STAs in the network, system has higher capacity of UL MU access.

The Figure 5.5 shows the latency per STA with different number of scheduled STAs. The conventional UORA (ungrouping) has quite high latency in the ultra-dense network due to the rapidly growing collision rate. The average latency per STA increases when the number of scheduled STA increase. The reason average latency rises with the number of scheduled STAs is that more scheduled STAs occupy more RUs in each group and there will be less RUs for random access. Because the total number of STA is much higher than the scheduled STAs with fixed number of scheduled STAs in the ultra-dense network, the average latency per STA is influenced more by random-access STAs. Even though the average latency is risen by total STA number, it is much better than the ungrouping UORA in the ultra-dense network. The grouping scheme optimizes the collision rate per group, the latency rises in a linear rate with rising number of total STAs.

The Figure 5.6 presents the QoS utility per STA with different number of scheduled STAs.

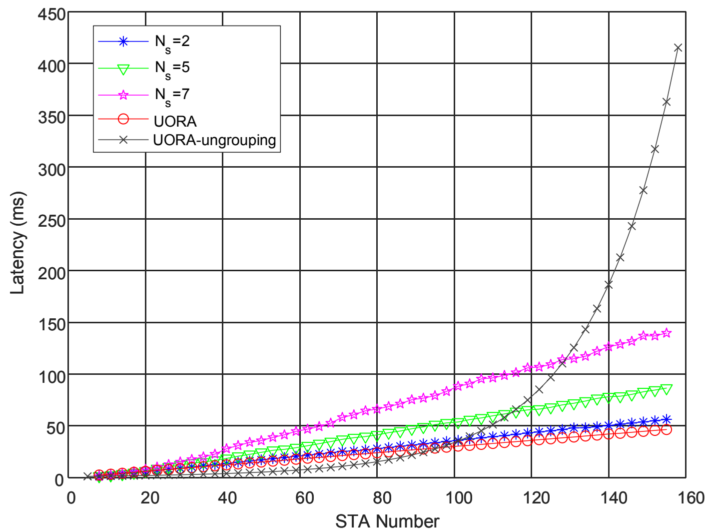

Figure 5.5: Latency of hybrid scheme with fixed number of scheduled STAs.

The QoS Utility reflect the preference of each QoS performance. In this thesis, we use the

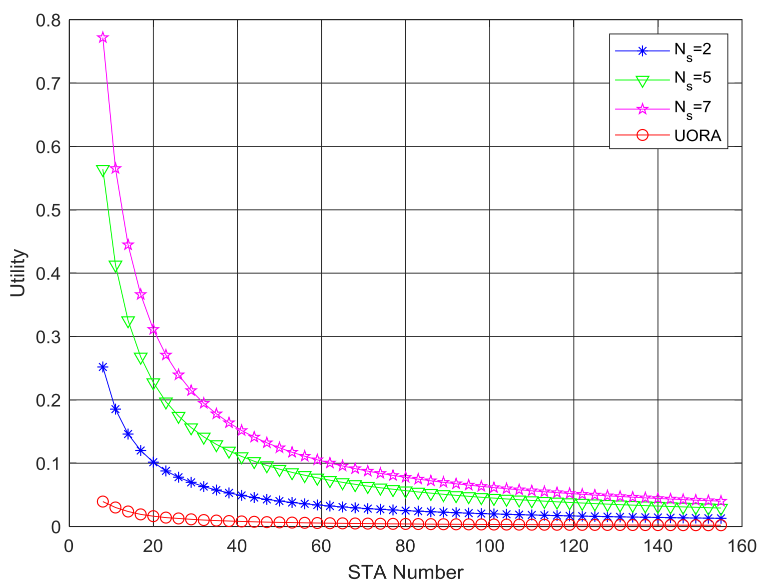

Figure 5.6: QoS utility of hybrid scheme with fixed number of scheduled STAs.

latency as an example. There are only two types of STAs for simplification. The average utility per STA rises when the number of scheduled STAs is higher. Because the latency sensitive STAs are selected as scheduled STAs, which means the performance of STAs that has higher weight is guaranteed. With more high weight STAs, the QoS utility is higher.

5.3.2 Proportional Number of Scheduled STAs

In the realistic networks, the number of scheduled STAs can not only be fixed constant, but also a dynamically changing variant. In this section, we suppose the number of scheduled STAs is a variant that has a proportional relationship with total STA number. Note that all simulation parameters are presented in Table 5.1, expect the number of scheduled STAs, which is expressed as:

$$N_s = \rho * N, \tag{5.22}$$

where ρ is the parameter that indicates the proportional rate of scheduled STA in the total STA. In this section, we assume this parameter as a variant to study how the variable number of scheduled STA influence the performance of system and each STA. The numerical results of BSR delivery rate with different ρ are presented in Figure 5.7.

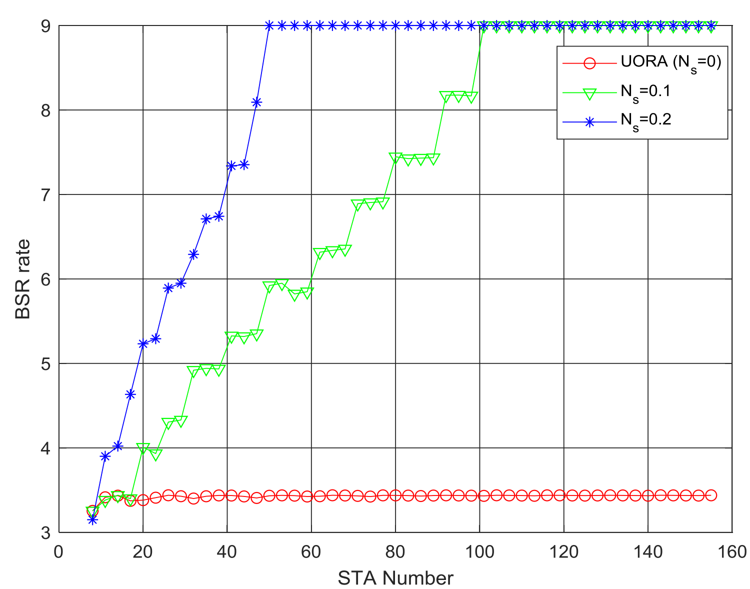

Figure 5.7: BSR delivery rate of hybrid scheme with variant number of scheduled STAs.

Different from the network with fixed number of scheduled STAs, the number of scheduled STAs in this network is proportionally changing with the total number of STAs. With more scheduled STAs participate in the transmission, the BSR delivery rate is rising at the same time. As is shown in Figure 5.7, the higher proportional rate leads to faster rising rate of BSR delivery rate. However, due to the limitation of the channel RUs, the maximum BSR delivery rate is equal to the number of RUs in this channel.

Even though the rising number of scheduled STAs improves the BSR delivery rate, it also reduces the number of RUs for random access, which sharply degrades the performance of random-access STA, the effect of which is presented in Figure 5.8.

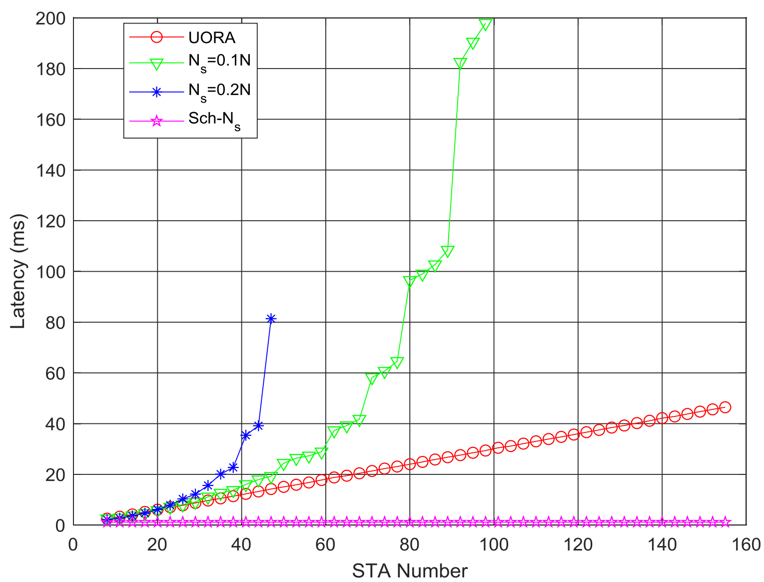

Figure 5.8: Latency of hybrid scheme with variant number of scheduled STAse.

Because the number of random access STA is usually much higher than the scheduled STAs, the degrading performance of random-access STA always leads to the performance of average STA declines. Even though the performance of scheduled STAs (pink line) is maintained in high level in the ultra-dense network, the average latency per STA sharply increasing as total STA number rising. Note that the curves of the average latency per STA stop in the middle of x-axis, which means the network can't support any more STAs to access the network, because all RUs are occupied by the scheduled STAs, the proposed hybrid scheme has worse average latency performance. Nevertheless, as is mentioned in Chapter 1, in the ultra-dense network, the wide application of IoT leads to the diversity of IoT service. Different services have different requirements and preference about the QoS performance. The average performance cannot properly reflect the quality of service on each device.

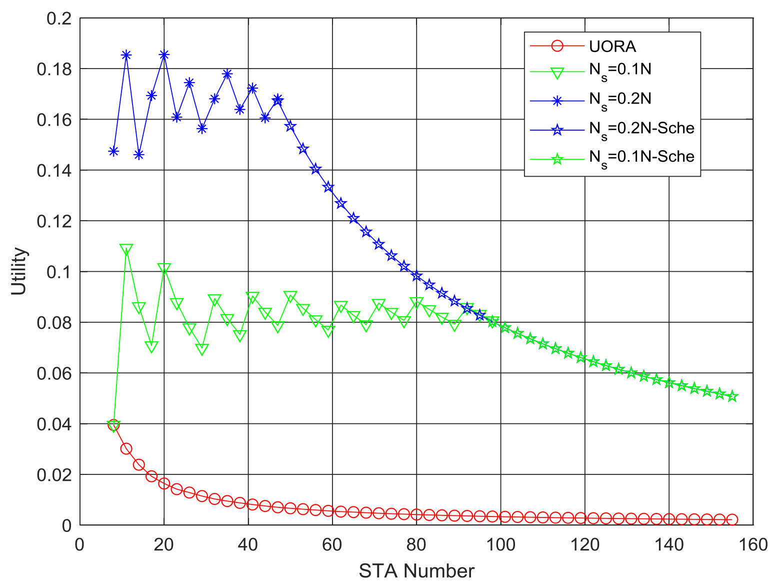

Figure 5.9: QoS utility of hybrid scheme with variant number of scheduled STAs.

In the proposed hybrid grouping scheme, the AP assigns the scheduled STAs according to the sensitivity about latency, the STAs that are sensitive to the latency are scheduled and have high level performance of latency, therefore the proposed hybrid scheme has a better performance than conventional UORA grouping scheme in QoS utility. In Figure 5.9, the performance of QoS utility is presented. The proposed hybrid grouping scheme has overwhelming performances than the conventional UORA grouping scheme. With more latency sensitive S-TAs served, the QoS utility is higher. The QoS utility decrease when the network can not support more STAs to access, but the average STA QoS still higher than the conventional UO-RA grouping.

5.3.3 Fix vs. Variable Number of Scheduled STAs

In this subsection, we will compare the different performance between fixed and variable number of scheduled STAs. The fixed number is $N_s = 5$, and the variable number is $N_s = 0.1N$.

Other simulation parameters are shown in Table 5.1. The latency performance of proposed algorithm compared with conventional UORA grouping is shown as follows.

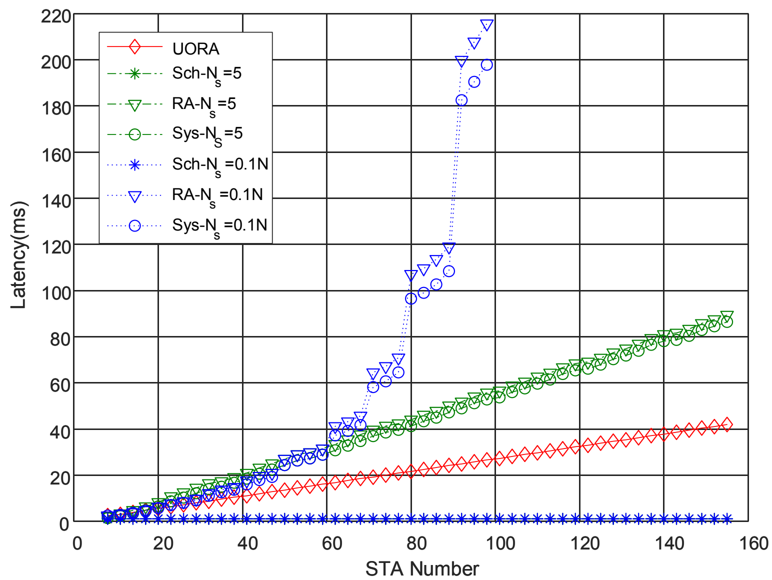

Figure 5.10: Latency of hybrid scheme with variant number vs. fixed number of scheduled STAs.

As is shown in Figure 5.10, the scheduled STAs occupy the RUs and the rest RU for random access is less than conventional UORA grouping scheme. Therefore, the average latency of hybrid scheme (green and blue lines) are higher than the conventional UORA. However, the latency performance of schedule STAs (blue line with star point) is guaranteed in very small value. Compared with the fixed number, the latency of variant number is increasing with the number of scheduled STAs. In Figure 5.11, the details of variant number scheme is presented. Note that the improvement of latency is limited when scheduled STA number is low, while it rises faster when the scheduled STA number is high. The reason why this happens is that when decreasing BSR delivery rate with increasing number of RUs in UORA mechanism, as well as the effect of the rising number of random-access STAs. Therefore, how to effectively schedule the hybrid grouping scheme using this property becomes a meaningful topic, which will be further studied in the future.

The BSR rate performance of proposed algorithm compared with conventional UORA grouping is shown in Figure 5.12.

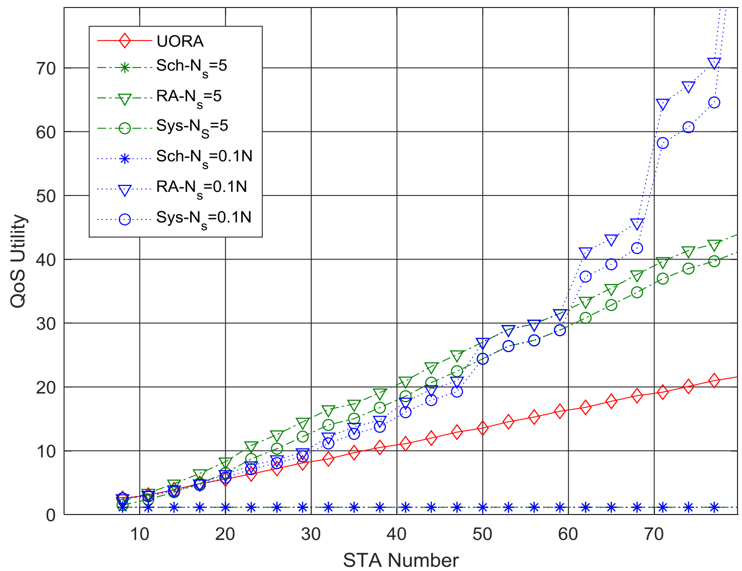

Figure 5.11: Latency of hybrid scheme with variant number vs. fixed number of scheduled STAs (zoom in).

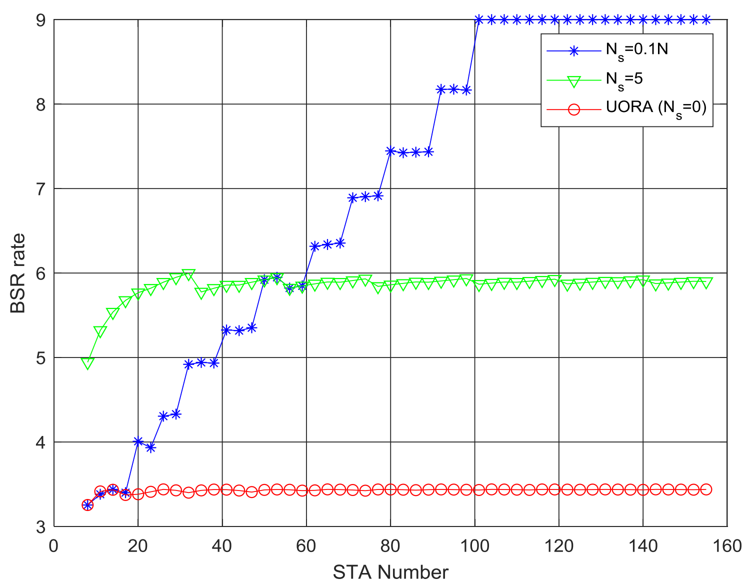

Figure 5.12: BSR delivery rate of hybrid scheme with variant number vs. fixed number of scheduled STAs.

Similar to latency performance, the BSR rate is also rising with the number of scheduled STAs. The numerical result of average utility of each STA is shown in Figure 5.13.

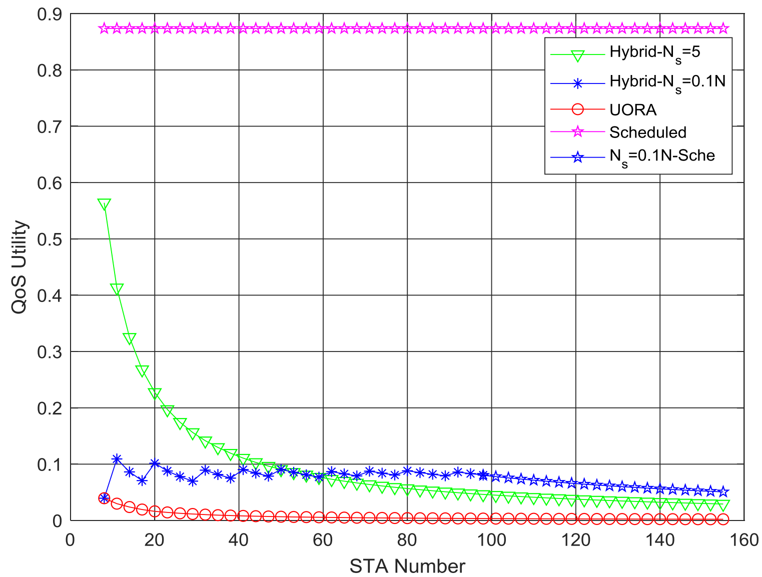

Figure 5.13: QoS utility of hybrid scheme with variant number vs. fixed number of scheduled STAs.

In Figure 5.13, the proposed hybrid grouping scheme has better QoS utility than conventional UORA grouping scheme, either in fixed or variable number scenario. Because the proposed scheme serves the more important STA and guarantees the latency of scheduled STAs, which are latency sensitive STAs. The utility of scheduled STAs is also presented in Figure 5.13 with the pink start line.

5.3.4 Different Access Frequency

This subsection considered the influence of different access frequency in the hybrid transmission scenario, the number of scheduled STAs $N_s = 5$ in this subsection, other factors are set with default value shown in Table 5.1. The average access frequency requirement is the mean value of all access frequency of STAs, which is expressed as:

$$f = \frac{1}{N_s} * \sum_{k=1}^{N_s} f_k. \tag{5.23}$$

In this thesis, the number of scheduled STAs N_s and the access frequency requirement of each scheduled STA f_k is regarded as the given constant, therefore f can be calculated as a constant. The BSR delivery rate with different access frequency is shown in Figure 5.14. With higher

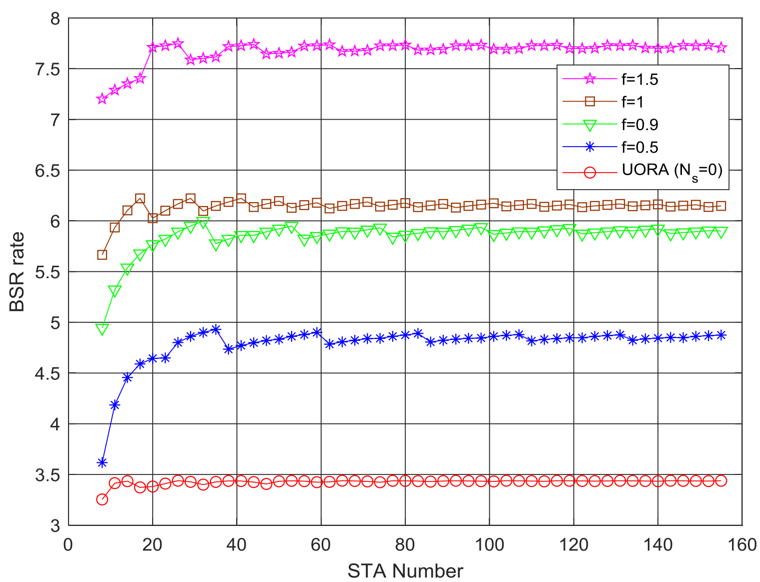

Figure 5.14: BSR delivery rate of hybrid scheme with different access frequency.

access frequency, the BSR rate is also higher. In the access model of proposed scheme, scheduled STAs are allowed to multiply access across different groups in one big group period. Note that random-access STAs need to wait one big group period after one transmission. The illustration of one big group period is shown in Figure 4.3. The higher access frequency represents this STAs are more frequently allocated, which means more RUs are occupied by scheduled STAs. Therefore, the performance of rising access frequency is similar to rising the number of scheduled STAs as is shown in Figure 5.4.

The Figure 5.15 shows the latency performance of hybrid grouping scheme with different access frequency.

The higher access frequency leads to the higher average latency per STA as is shown in Figure 5.15. The reason why this happens is similar to rising rate of BSR. The increasing number of frequency means more RUs are occupied by scheduled STAs, so the number of rest RUs becomes less and the performance of random-access STAs become worse. Because

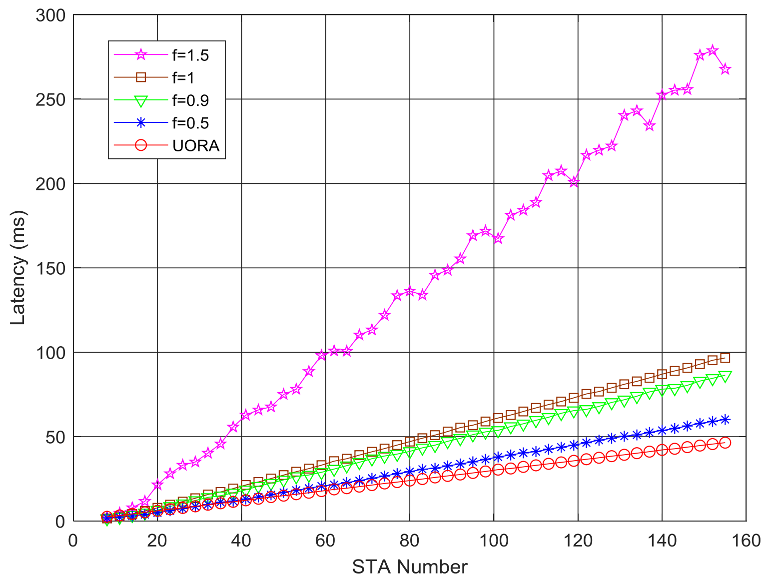

Figure 5.15: Latency of hybrid scheme with different access frequency.

the number of random-access STAs is the majority STAs, the average latency performance per STA in the system increases with the rise access frequency. The Figure 5.16 shows the QoS utility with different access frequency.

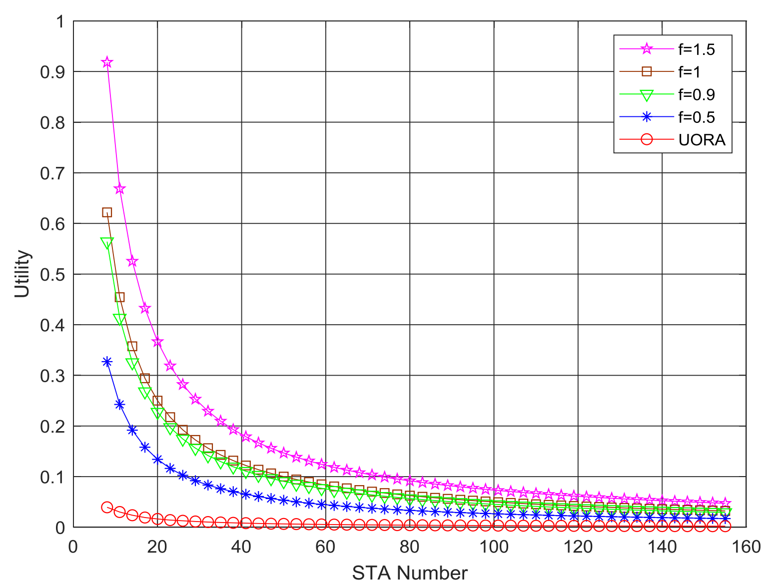

Figure 5.16: QoS utility of hybrid scheme with different access frequency.

The high access frequency leads to high QoS utility, because more RUs are assigned to STAs that are more sensitive to the latency. This allocation scheme of STAs is more effective than fair allocation such as UORA grouping. Changing the access frequency has similar function as changing scheduled STAs' number. These two factors can be considered together when facing different network scenarios. For instance, the network that has a large number of scheduled STAs' number with low access frequency, can perform the same (or similar) way as the network that has a small number of scheduled STAs' number with high access frequency. The differences are that the first scenario can serve more scheduled STAs and the second scenario can improve the QoS utility for particular scheduled STAs. Therefore, how to balance these two characters become an interesting topic, which will also be studied in the future.

5.3.5 Different Length of Packet

In this subsection, we will discuss the influence of different data packet length in the hybrid transmission scenario. For simplification, there are two types of payload, assume that the data frame with 8000 bites payload is the large data frame, and the data frame with 1000 bites payload is the small data frame. Other parameters are set with default value shown in Table 5.1. Because the BSR delivery rate only reflects the information soliciting efficiency in the information soliciting stage of BTM, we directly study the throughput to evaluate the impact of different payload length on the system. The performance of system throughput of the hybrid scheme with different payload length is presented in Figure 5.17.

The large payload has the better performance of system throughput in all kinds of access mechanism mentioned in this thesis, and the BTM grouping scheme has the performance that is close to theoretical PHY rate (11.8Mbps) with large payload, as is shown in Figure 5.17. The performance of small payload has worse performance than large payload because the large payload eases the impact of the overhead and control signal in transmission. However, using large payload does not have the overwhelming advantages, it also has drawbacks. As is shown in Figure 5.18, which shows the latency of hybrid scheme with different payload length.

The latency of length payload (line with stars) is much higher than the short payload (line with circles). The long payload duration has advantages as well as drawbacks in transmission.

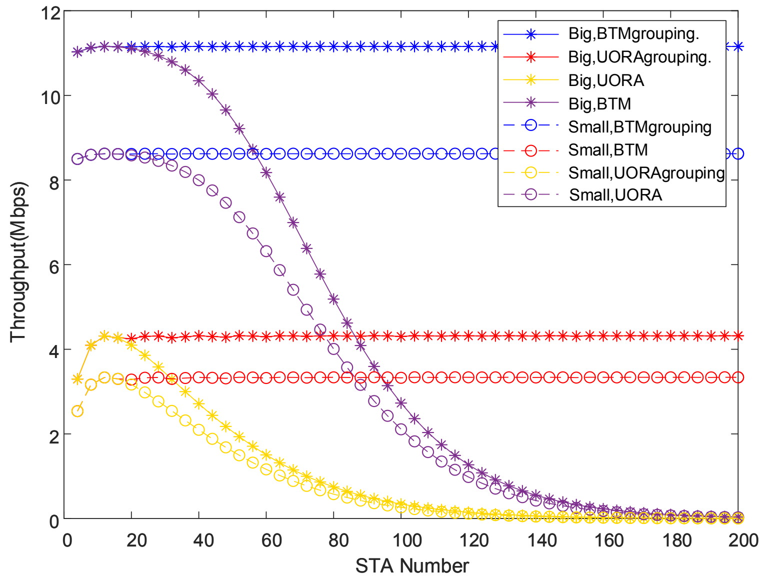

Figure 5.17: Throughput of hybrid scheme with different payload length.

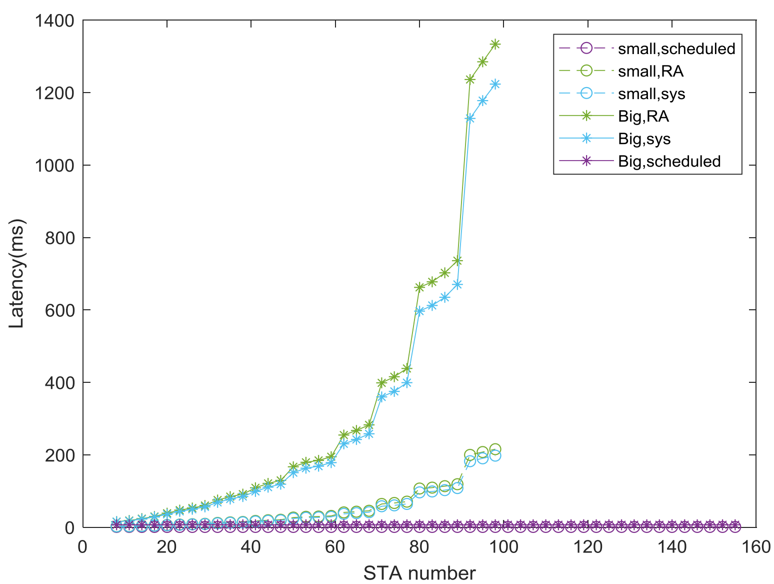

Figure 5.18: Latency of hybrid scheme with different payload length.

For sure the long payload increases the proportion of data transmission time, it also increases the total transmission time for each data frame. In the grouping scheme proposed in this thesis, AP allocates transmission time periods to each group by Round Robin method, so the longer transmission duration of each group accelerate with group number and lead to much higher delay. Therefore, there is a trade-off when choosing large payload or small payload, which should be decided according to the specific implementation in the realistic world, which is also worth to be studied in the future. In the Figure 5.19, the QoS utility of hybrid scheme with different payload length is presented.

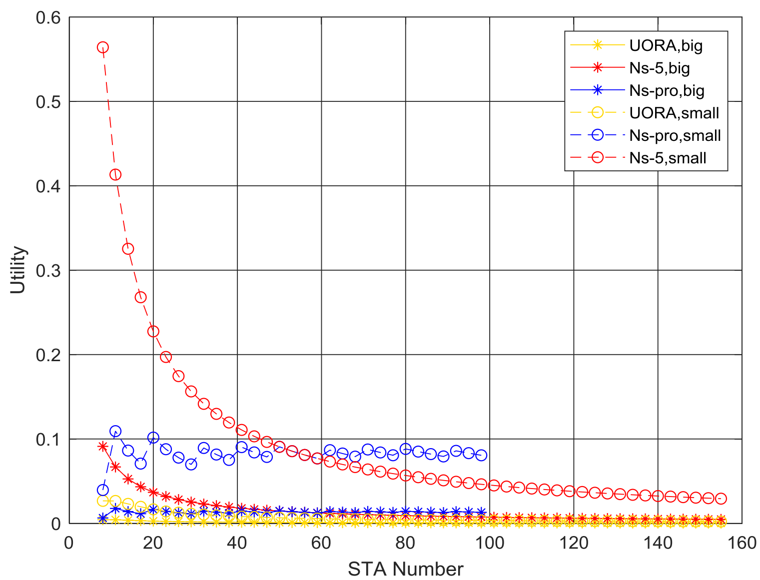

Figure 5.19: QoS utility of hybrid scheme with different payload length.

The small payload has the overall better latency performance than the large payload, which is also reflected in the QoS utility. The small payload has overwhelming latency performance than large payload, whether in the hybrid grouping scheme or the UORA grouping scheme.

5.4 Summary of the Chapter

A new Hybrid BTM grouping scheme is proposed in this chapter, the system model is formulated and a hybrid grouping algorithm is proposed to implement this scheme. The proposed algorithm provides lower latency experience for scheduled STAs by allowing scheduled STAs cross-group access multiple times cross the groups in one big grouping period. Meanwhile, the proposed grouping algorithm improves the QoS performance by assigning the latency sensitive STAs as scheduled STAs. The performance of proposed Hybrid BTM grouping scheme and algorithm is valid by numerical results with different dimensions of performances and considering diverse factors that influence these performances.

Chapter 6

Conclusion and Future Works

6.1 Conclusion

This thesis mainly studied two major challenges in the UL MU transmission of 802.11ax, e.g. the performance optimization in the ultra-dense networks; and the QoS utility enhancement with the diverse service requirement. In order to achieve these goals, we proposed UORA grouping scheme, BTM grouping scheme and Hybrid BTM grouping scheme in Chapter 3 to 5, with three grouping and resource allocation algorithms.

We firstly studied the relationship between RU efficiency with STA number in the UORA network in Chapter 3. The rising STA number leads to the high collision rate in the ultra-dense network, which degrades the performance of the whole system and each STA, such as RU efficiency and throughput. Therefore we proposed a grouping UORA scheme ease the high collision rate and maintain the performance in the ultra-dense network. In this scheme, STAs are virtually divided into different groups along the time dimension using TWT mechanism. Meanwhile, in order to optimize the system efficiency as well as eliminate the influence of remainder when grouping, an adaptive grouping algorithm is designed to facilitate AP grouping STAs. The numerical results show that the proposed adaptive grouping scheme significantly enhanced the performance of both system and each STA.

In Chapter 4, we considered the limitation of RU efficiency using UORA mechanism, proposed and studied the grouping scheme in BTM. An averagely resource allocation method is adopted for RU allocation in BTM. The numerical results show that the BTM grouping scheme is superior to conventional BTM mechanism and the proposed UORA grouping scheme.

At last, a Hybrid BTM Grouping scheme is proposed to support the diversity of services operated on different devices in Chapter 5. The QoS utility is used to evaluated the satisfaction and preference of different QoS performance. We used the latency as an example, divided STAs into two types: latency sensitive (with high utility weight) STAs and latency non-sensitive (with low utility weight) STAs. In order to improve the QoS experience of latency sensitive STAs, we proposed a Hybrid BTM Grouping to scheduled the grouping and access scheme. The proposed algorithm allows scheduled STAs multiply access the AP across the groups. The performance of proposed scheme is evaluated by the numerical results, which show the proposed Hybrid BTM grouping scheme has better performance in BSR delivery rate and QoS utility than the BTM grouping.

6.2 Future Works

In the future IoT networks, there are diverse of devices connected and different types of services operated. In this thesis, we only use latency as the example to study the utility of QoS, while in the realistic IoT network, each kind of service is supported by multiple dimension of QoS performance. Therefore, how to schedule the limited network resources to maximally satisfy the services with multi-domain requirements is a interesting and meaningful topic. The potential research topics are introduced as follows.

- Utility optimization in diverse IoT network

  Dynamical weight in utility QoS function. In Chapter 5, we suppose that STAs have constant linear preference wight in the utility function. Even though this model simplify the calculation of utility of each STA, it is difficult to describe the dynamical changing QoS preference of STA in the realistic world. Therefore, the Non-linear relation ship in utility function should be considered to describe the dynamical preference of QoS in the future works.

  Multiple dimension of QoS. We only considered one QoS character-latency in Chapter 5. While the service experience is influenced by multiple dimensions of QoS factors, including throughput, power consumption, reliability, privacy, security etc. Therefore, more dimension should be considered into the QoS utility function.

Diversity of service requirements. In the ultra-dense network with the diversity of IoT devices, there are diverse services operated on these devices. Each service has there own preference (utility function curve) with different QoS factors. How to optimize the Utility of the STAs in the network in worth to study.

- Preference study, awareness and prediction.

  In Chapter 5, the QoS requirements are quantified by the "weight" in the utility function. These requirements are also normalized, we suppose the sum of these "weight" is 1, which means we regard all services as the same. Each service can freely allocate these "weight" according to its requirement. With the multiple dimension of QoS, one service may allocate some QoS performances higher "weight", we call this service "prefer" these performance than other performance, or simplified as "preference".

  With different preferences of each service, when smart IoT devices are optimizing its service quality, the behaviors of these devices may different from conventional STAs in the wireless network. How this "preference" influences the performance of the whole network and each device is a topic that is worth to be studied.

  Meanwhile, devices have no or few information about other devices' "preference". This information asymmetry leads to low efficiency in the network scheduling. How these "preference" is able be awareness by each devices is also an interesting topic.

  Generally, the "preference" of devices are dynamically changing, which will highly increase the complexity of network scheduling. Find a reliable method to predict "preference" of each devices can also enhance the performance of the whole network and each device.

- Adaptive Self-organized smart scheduling networks structure.

  Even with the prediction of utility function, the optimizing is still a high cost operation for AP. With the known preference of each service as well as the AI operated each device, it is able to allow the devices participating the network scheduling to enhance the performance of the network. In this scenario, designing a network structure that is able to allow AI device participating in the network management, becomes a effective way to reduce the scheduling pressure in AP side.

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